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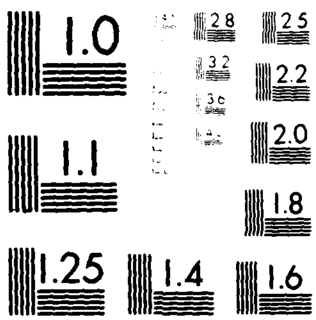

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A DYNAMICAL MODEL FOR PREDICTION OF FORMATION, GROWTH AND DISSIPATION OF A CLOUD

Final Technical Report

by

Louis Berkofsky

May 1982

EUROPEAN RESEARCH OFFICE

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The Jacob Blaustein Institute for Desert Research
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A dynamical model for the prediction of the life cycle of a desert cloud has been developed. The cloud is assumed to be a plume, i.e., to be contained within a cylindrical axi-symmetric volume. Thus, given ambient atmospheric conditions, and appropriate initial and boundary conditions, it is possible to predict the evolution as a function of height of a cloud. In all cases which we tested, the initial and ambient data were such that the life cycle never exceeded a few minutes. This is probably due to the fact that the data were

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XX. Abstract (continued)

compatible with a dry environment, thus preventing development. It is shown how this model may be interlaced with one for the larger scale circulation, thus providing the possibility for the prediction of moisture convergence, necessary for cloud formation.

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Introduction

The problem of the formation, growth, and dissipation of a cumulus cloud is so complex, that it has so far defied solution. The cumulus cloud is a three-dimensional space phenomenon, and should be treated as such. During the last few years, several three-dimensional convection models have been constructed (Williams, 1969: Deardorff, 1970: Fox, 1972: Steiner, 1973: Wilhelmson, 1974: Miller and Pearce, 1974: Schlesinger, 1975:). The number of models has not been great, mainly because they demand cumbersomely large amounts of computing storage and expenditures if adequate spatial resolution is to be achieved. Indeed, even in the most sophisticated model, i.e., that of Schlesinger (1975), the calculations had to be limited to preliminary "midget" experiments with sufficiently few grid-points to circumvent these demands.

By contrast, in recent years, a number of two-dimensional models have been developed for the study of deep precipitating convective clouds (Takeda, 1966: Orville and Sloan, 1970b: Schlesinger, 1973a, b: Hane, 1973). Two-dimensional axisymmetric models have also been developed (Ogura, 1963: Murray, 1970: Soong and Ogura, 1973). These models demand far less computer time than three-dimensional models, and are able to reproduce many important features of the cumulus cloud. Even simpler, less time consuming models are "quasi-two-dimensional" models (Weinstein and Davis, 1968: Berkofsky, 1974: Simpson and Dennis, 1975). Such models have given remarkably reasonable results in cumulus dynamics studies, especially when used for operational purposes.

In view of the above comments, and in view of the fact that little work has been done in this area relative to desert cumulus, the approach to be taken here will be to develop, at first, a "quasi-two-dimensional" model, and then go on to more sophisticated models.

The purpose of the current proposed research is to develop a model for the prediction of the formation, growth and dissipation of a cumulus cloud in a desert region. The investigation of cumulus clouds is important because such clouds release large amounts of energy, especially in tropical and sub-tropical latitudes, and thereby profoundly influence the atmospheric circulation in those regions. Furthermore, there are certain practical advantages in being able to predict the development of desert cumulus clouds. As rainfall is sparse and spotty in desert areas, there would accrue profound advantages to the agriculture and other aspects of the economy of such regions if the occurrence or non-occurrence, and the location of precipitation, could be predicted. Additionally, the ability to predict intensity and amount of rainfall would be extremely important in relation to desert floods. Finally, a by-product of such studies would be the ability to consider weather modification possibilities.

Cloud Model and Equations

We shall consider a cloud model in which the variables are functions of height, z, and time, t. The model is axisymmetric, but the radius of the cloud is itself allowed to vary with height. Thus the cloud model has the characteristics of a "plume" model. The system to be studied has the following main assumptions implicit in it.

1. Cloud is condensed water that fully shares the air motion.
2. Cloud forms in rising saturated air and evaporates in descending air at the rate $-w\rho\frac{dq_s}{dz}$ where q_s is the saturation mixing ratio of water in air, w is the vertical velocity of the air, ρ is the air density. Cloud-containing air is always saturated, and unsaturated air never contains clouds.
3. Cloud changes to raindrops that are distributed in size according to an inverse exponential distribution at the rate $k_1(\rho Q_c' - a)$ where the magnitude of k_1 and a may be selected to simulate various processes and rates. Q_c' is the "cloud water" - water which is condensed in the updraft, forms very small droplets which have a negligible terminal velocity and are thus totally carried along by the updraft. $k_1(\rho Q_c' - a)$ is called "conversion".
4. Precipitation particles once formed are assumed to be distributed in size according to an inverse exponential law and to collect cloud particles or evaporate in subsaturated air according to approximations to the natural accretion and evaporation processes. This is called the "collection" process.

To derive the appropriate equations for the model, we begin by defining

$$dmc = dm_+ - dm_- \tag{1}$$

[see Ooyama (1971)], where dm_c represents the change of mass of a rising plume as the net result of entrainment dm_+ and detrainment dm_-. Thus, as the mass rises from z to z+dz its mas increases from m to m+dm. In general, it is assumed that entrained air brings α_e into the plume (α is a scalar, and e means environment) and the detrained air takes α_c (c means cloud) out of it. Therefore, if α is a conservative property, the general conservation law is written:

$$\left.\begin{aligned} d(\alpha_c m_c) &= \alpha_e\, dm_{c+} - \alpha_c\, dm_{c-} \\ &\text{or} \\ m_c\, d\alpha_c &= -(\alpha_c - \alpha_e)\, dm_{c+} \end{aligned}\right\} \tag{2}$$

Writing T (temperature) for α, and multiplying Equation (2) by C_p, we find

$$(dh)_s = c_p m_c dT = -c_p (T_c - T_e)\, dm_{c+} \tag{3}$$

where $(dh)_s$ means sensible heat gain or loss due to entrainment, c_p is specific heat at constant pressure. Similarly,

$$(dh)_L = L m_c dq_c = -L(q_s - q_e)\, dm_{c+} \tag{4}$$

where $(dh)_L$ is a heat loss, L is latent heat of condensation, q is mixing ratio. The heat loss is due to evaporation of liquid water necessary to resaturate the air which has become slightly subsaturated due to entrainment.

When the supercooled water in the parcel is frozen, there are two more non adiabatic heat transfer terms to be considered. The first is the heat gained due to the release of latent heat of fusion.

$$(dh)_f = m_c L_f Q', \tag{5}$$

where L_f is the latent heat of fusion, and Q' is the amount of supercooled water that is frozen, in units of grams of water per gram of air. Here

$$Q' = Q_c' + Q_h' \tag{6}$$

where Q_c' is cloud water, i.e. the water condensed in the updraft, having negligible terminal velocity, and totally carried along by the updraft. Q_h' is called hydrometeor water, i.e. a class of drops which have grown from Q_c' due to contained condensation, which have important terminal velocity. The process by which hydrometeor water is formed is called conversion.

Before freezing occurs, the liquid water and water vapor in the parcel are in vapor equilibrium at the saturation vapor pressure over a water surface. Immediately after freezing has occurred, a similar equilibrium must be achieved between the newly formed ice and the vapor. Since the saturation vapor pressure over an ice surface is less than over a water surface at the same temperature and pressure, there must be a deposition of vapor onto the ice. The heat gained by the parcel by this deposition is

$$(dh)_d = m_c L_s (\Delta q_s)_{water \to ice} \tag{7}$$

where L_s is the latent heat of sublimation, and $(\Delta q_s)_{water \to ice}$ is the difference between the saturation mixing ratio over a water surface and that over an ice surface.

The first law of thermodynamics is

$$dh = \left(c_p\, dT - \frac{1}{\rho} dp\right) m_c \tag{8}$$

where dh is the heat gained or lost by non-adiabatic processes, is air density, is pressure.

Using the hydrostatic relation only at this point,

$$dp = -\rho g\, dz \tag{9}$$

we can substitute Equations (3), (4), (5), (7), (9) into Equation (8) to obtain

$$\frac{dT_c}{dt} = -w_c \frac{\left[\frac{A_1 g}{c_p}\left(1 + \frac{q_s L J}{R T_c}\right) + \mu (T_c - T_e) + \mu \frac{L}{c_p}(q_s - q_e)\right]}{\left(1 + \epsilon \frac{L^2 q_{sc}}{c_p R T_c^2}\right)} \tag{10}$$

$$+ \frac{1}{c_p dt} \frac{\left[L_f Q' + L_s (\Delta q_s)_{water \to ice}\right]}{\left(1 + \epsilon \frac{L^2 q_s}{c_p R T_c^2}\right)}$$

where A_1 is the heat equivalent of work, $J = \frac{1}{A_1}$ = mechanical equivalent of heat, $\epsilon = 0.621$.

Here $$\mu = \frac{1}{m_c}\frac{d m_c}{dz} \qquad (11)$$

We shall derive an expression for μ later.

The above Equation (10) for the rate of change of temperature within the cloud reduces to the equation for the pseudo-adiabatic lapse rate when there is no entrainment (μ=0), and we write

$$\frac{dT}{dt} = \frac{1}{w}\frac{dT}{dz} \qquad (12)$$

where w is the vertical velocity of the parcel.

The well-known Clapeyron equation may be written

$$\frac{dq_s}{dt} = \frac{q_s}{RT_c}\left(g w_c + \frac{\epsilon L J}{T_c}\frac{dT_c}{dt}\right) \qquad (13)$$

One way of deriving the cloud water equation is to apply Equation (1) to the sum of vapor and cloud water within the cloud (where $q_c = q_s$ by assumption),

$$d\left[(q_s + Q_c')m_c\right] = (q + Q_c')_e\, dm_{c+} - (q + Q_c')_c\, dm_{c-} \qquad (14)$$

Since $Q'_{ce} = 0$ = convective cloud water in the environment,

$$\frac{dQ_c'}{dt} = -\frac{dq_s}{dt} - \mu w_c (q_s - q_e + Q_c') \qquad (15)$$

If we assume that is is permissible to add the collection and conversion terms (to be specified explicitly below), even though they destroy the conservation properties to some extent, we get

$$\frac{dQ_c'}{dt} = -\frac{dq_s}{dt} - \mu w_c (q_s - q_e + Q_c') \text{ -conversion - collection} \qquad (16)$$

A more sophisticated treatment starts from the equations of Kessler (1969).

$$\frac{\partial Q_c}{\partial t} = -u\frac{\partial Q_c}{\partial x} - v\frac{\partial Q_c}{\partial y} - w\frac{\partial Q_c}{\partial z} + w\left(Q_s\frac{\partial \ln\rho}{\partial z} - \frac{\partial Q_s}{\partial z}\right) + Q_c w\frac{\partial \ln\rho}{\partial z} - k_1(Q_c - a) - k_2 Q_c Q_R^{7/8}\left(\frac{\rho_0}{\rho}\right)^{\frac{1}{2}} \qquad (17)$$

and

$$\frac{\partial Q_h}{\partial t} = -u\frac{\partial Q_h}{\partial x} - v\frac{\partial Q_h}{\partial y} - (V+w)\frac{\partial Q_h}{\partial z} - Q_h\frac{\partial V}{\partial z} + Q_h w\frac{\partial \ln \rho}{\partial x}$$
$$+ k_1(Q_c - a) + k_2 Q_c Q_h^{7/8}\left(\frac{\rho_B}{\rho}\right)^{1/2} \qquad (18)$$

In these equations, Q_c, Q_h, Q_s are the cloud water, hydrometeor water, and cloud water vapor, respectively, measured in gm m^{-3}. They are related to Q_c', Q_h', q_s by

$$\left.\begin{aligned} Q_c &= \rho\, Q_c' \\ Q_h &= \rho\, Q_h' \\ Q_s &= \rho\, q_s \end{aligned}\right\} \qquad (19)$$

The terms involving k_1 and k_2 are empirically derived for the calculation of conversion and collection, respectively. V is the terminal velocity of liquid water droplets. It is related to Q_h' by

$$V = -130 K_3 (Q_h')^{0.125}, \qquad (20)$$

where K_3 is a constant,

$$K_3 = \begin{cases} 15.39, & T > 273°K \\ 11.58, & T \leq 273°K \end{cases} \qquad (21)$$

ρ_B is the density at the base of the cloud.

We may relate the horizontal transport terms to the entrainment in the following heuristic fashion.

In cylindrical coordinates

$$-\left(u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y}\right)(Q_c + Q_s) = u_r\frac{\partial}{\partial r}(Q_c + Q_s)$$
$$\simeq u_r\frac{\left[(Q_c+Q_s)_e - (Q_c+Q_s)_i\right]}{\Delta r} \qquad (22)$$

where U_r is the inward directed velocity, and where the subscripts e and i refer to the outer edge and the center of the cloud, respectively. Thus $\Delta r = r$ = radius of cloud.

Since $Q_{ce} = 0$,

$$-u_r\frac{\partial}{\partial r}(Q_{c_i} + Q_{s_i}) \approx -\frac{u_r}{r}\left[(Q_{si} - Q_{se}) + Q_{c_i}\right] \qquad (23)$$

If we put, for the time being,

$$u_r \sim \alpha w_{c_i} \quad , \frac{\alpha}{r_i} = \mu_i \tag{24}$$

(These assumptions will be discussed later in connection with entrainment), then

$$-\left(u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y}\right)\left(Q_{c_i} + Q_{s_i}\right) \approx -\mu_i w_{c_i}\left[Q_{c_i} + \left(Q_{s_i} - Q_e\right)\right] \tag{25}$$

Similarly,

$$-\left(u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y}\right)Q_{\ell_i} \approx -\mu_i w_{c_i} Q_{\ell_i} \quad , \tag{26}$$

since $Q_{he} = 0$.

Then the equations for Q_c' and Q_h' become

$$\frac{dQ_c'}{dt} = -\frac{dq_s}{dt} - \mu w_c\left[(q_s - q_e) + Q_c'\right] - k_1\left(Q_c' - \frac{a}{\rho_c}\right) - k_2\rho_c^{7/8}\left(\frac{\rho_\ell}{\rho_c}\right)^{1/2} Q_c'(Q_\ell')^{7/8} \tag{27}$$

and

$$\frac{dQ_\ell'}{dt} = \frac{w_c}{(V+w_c)}\left[-Q_\ell\left(V\frac{d\ln\rho_c}{dz} + \frac{dV}{dz}\right) - \mu w_c Q_\ell' + k_1\left(Q_c' - \frac{a}{\rho_c}\right) + k_2\rho_c^{7/8}\left(\frac{\rho_\ell}{\rho_c}\right)^{\frac{1}{2}} Q_c'(Q_\ell')^{7/8}\right] \tag{28}$$

In this formula, we assume $d\ln\rho/dz \approx \partial\ln\rho_c/\partial z$, $dV/dz \approx \partial V/\partial z$

To derive the equation for the vertical velocity. we consider the third equation of motion

$$\frac{dw}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g - \text{drag} \tag{29}$$

Assuming that the environment is in hydrostatic equilibrium, that the pressure gradient of the perturbation ($1/\rho\,\partial p'/\partial z$) can be neglected compared with that of the environment, and that the drag forces include those due to Q_c' and Q_h', Equation (29) may be written.

$$\frac{dw_c}{dt} = g\left[\frac{(1+0.61q_s)T_c - (1+0.61q_e)T_e}{(1+0.61q_e)T_e} - Q_c' - Q_\ell'\right] - \mu w_c^2 \tag{30}$$

In Equation (24), we have (tentatively) assumed

$$\mu = \alpha/r$$

Then we need an equation for r. We derive a continuity equation starting with

$$M_{c_i} = \frac{dm_{c_i}}{dt} = \pi r_i^2 \rho_i w_{c_i} \tag{31}$$

Then

$$\frac{dM_{c_i}}{dz} = \frac{d}{dz}\left(\pi r_i^2 \rho_i w_{c_i}\right) \tag{32}$$

[See Warner (1970)]. Let the average radial velocity around a given cross-section of cloud be U_r. Then the average inflow is $U_r ds$. The actual inflow is

$$\int_0^{2\pi} u\, ds \approx 2\pi r u_r . \tag{33}$$

Now assume that the average radial velocity is proportional to the vertical velocity in the center of the plume,

$$u_r \approx q\, w_{c_i} \tag{34}$$

Since $u_r = q\, w_{c_i}$, the entrainment is

$$2\pi r_i u_r = 2\pi r_i q\, w_{c_i} .$$

The flow of mass into the cloud is then

$$2\pi r_i q\, w_{c_i} \rho_e \quad \mathrm{gm\ cm^{-1} sec^{-1}}$$

Thus the convergence of mass flux is

$$\frac{dM_{c_i}}{dz} = 2\pi r_i q \rho_e w_{c_i} \tag{35}$$

Using the definition of dM_{c_i}/dz in Equation (32), carrying out the indicated differentiation, assuming $\rho_e \sim \rho_i$, and dividing by M_{ci}, we find

$$\frac{dr_i}{dt} = q\, w_{c_i} - \frac{w_{c_i} r_i}{2}\left(\frac{d \ln w_{c_i}}{dz} + \frac{d \ln \rho_i}{dz}\right). \tag{36}$$

If we calculate

$$\frac{1}{M_{c_i}} \frac{dM_{c_i}}{dz} = \frac{1}{\pi r_i^2 \rho_i w_{c_i}} \frac{d}{dz}\left(\pi r_i^2 \rho_i w_{c_i}\right), \tag{37}$$

we find

$$\frac{1}{M_c}\frac{dM_c}{dz} \sim \frac{2\alpha}{R_i} \quad (38)$$

w assume that

$$\mu = \frac{1}{M_c}\frac{dM_c}{dz} = \frac{1}{M_{ci}}\frac{dM_{ci}}{dz} = \frac{2\alpha}{R} \quad (39)$$

Perkey and Kreitzberg (1972)].

Equations (10), (13), (20), (27), (28), (30), (36), (39) form the system the unknowns $T_c, q_s, V, Q_c', Q_\ell', w_c, R_c, \mu$. In solving the time dependent s of these equations, we write $d/dt = \partial/\partial t + w\,\partial/\partial z$

e we have already related horizontal transport to entrainment.

ical Equations

We list these in the order and in the form in which they will be solved

$$q^n_{si\,water} = q^n_{si} = \frac{\epsilon}{p^n_i}\left[10^{-\frac{2937.4}{T^n_i} - 4.9283\log T^n_i + 22.5518}\right] \quad (40)$$

$$q^n_{si\,ice} = \frac{\epsilon}{p^n_i}\left[10^{-\frac{2667}{T^n_i} + 9.5553}\right] \quad (41)$$

$$(\Delta q_{si})^n_{water \rightarrow ice} = q^n_{si\,water} - q^n_{si\,ice} \quad (42)$$

e n means time step and i means level. Here p is pressure and $\epsilon = .621$.

$$)^\circ = (w_i^2)^\circ + 2g\Delta z\left[\frac{(1+0.61q^n_{si})T^\circ_i - (1+0.61q_{ei})T_{ei}}{(1+0.61q_{ei})T_{ei}} - (Q'_{ci} + Q'_{\ell i})^\circ\right] - 2\mu(w_i^2)^\circ\Delta z \quad (43)$$

$$= R^\circ_i + \alpha\Delta z - \frac{R^\circ_i}{2}\left[(\ln w^\circ_{i+1} - \ln w^\circ_i) + (\ln \rho^\circ_{i+1} - \ln \rho^\circ_i)\right] \quad (44)$$

$$\rho^\circ_i = \frac{p^\circ_i}{RT^\circ_i} \quad (45)$$

$$^\circ_i = p_B \exp\left(-\frac{g}{R}\sum_{z_B}^{z}\frac{\Delta z}{T^\circ_i}\right), \quad \rho_B = \frac{p_B}{RT_B} \quad (46)$$

$$\mu_i^n = \frac{2\alpha}{R_i^n} \tag{47}$$

$$\frac{T_i^{n+1} - T_i^n}{\Delta t} + w_i \frac{\Delta T}{\Delta Z} = -w_i^n \frac{\left[\frac{A_1 g}{c_p} \frac{(1+q_{si}^n LJ)}{RT_i^n} + \mu_i^n (T_i^n - T_{ei}) + \mu_i^n \frac{L}{c_p}(q_{si}^n - q_{ei})\right]}{\left[1 + \frac{\epsilon L^2 q_{si}^n}{c_p R (T_i^2)^n}\right]} + \frac{1}{c_p \Delta t} \frac{\left[L_f (Q_{c_i}'^{\,n} + Q_{\ell_i}'^{\,n}) + L_s (\Delta q_{si})^n \text{ water} \rightarrow \text{ice}\right]}{\left[1 + \frac{\epsilon L^2 q_{si}^n}{c_p R (T_i^2)^n}\right]} \tag{48}$$

$$T_i^{n+1} = T_i^n - w_i^n \frac{\Delta t}{\Delta Z} \Delta T - w_i^n \Delta t \frac{\left[\frac{A_1 g (1+q_{si}^n LJ)}{c_p \, RT_i^n} + \mu_i^n (T_i^n - T_{ei}) + \mu_i^n \frac{L}{c_p}(q_{si}^n - q_{ei})\right]}{\left[1 + \frac{\epsilon L^2 q_{si}^n}{c_p R (T_i^2)^n}\right]} + \frac{1}{c_p} \frac{\left[L_f (Q_{c_i}'^{\,n} + Q_{\ell_i}'^{\,n}) + L_s (\Delta q_{si})^n \text{ water} \rightarrow \text{ice}\right]}{\left[1 + \frac{\epsilon L^2 q_{si}^n}{c_p R (T_i^2)^n}\right]} \tag{49}$$

$$\begin{aligned}(Q_{c_i}')^{n+1} = {} & (Q_{c_i}')^n - w_i^n \frac{\Delta t}{\Delta Z}(Q_{c_{i+1}}' - Q_{c_i}')^n - \frac{g w_i^n q_{si}^n}{R T_i^n} \Delta t \\ & - \frac{\epsilon LJ q_{si}^n}{RT_i} \Delta t \left[\frac{(T_i^{n+1} - T_i^n)}{\Delta t} + \frac{w_i^n}{\Delta Z}(T_{i+1}^n - T_i^n)\right] - \mu_i^n w_i^n \Delta t \left[(q_{si}^n - q_{ei}) + (Q_{c_i}')^n\right] \\ & - k \, \Delta t \left[(Q_{c_i}')^n - \frac{a}{\rho_i^n}\right] - k_2 \Delta t \left[\left(\frac{\rho_0}{\rho_i}\right)^n\right]^{\frac{1}{2}} (\rho_i^n)^{7/8} (Q_{c_i}')^n \left[(Q_{\ell_i}')^n\right]^{7/8}\end{aligned} \tag{50}$$

$$V_i^n = -130 \, K_s \left[(Q_{\ell_i}')^n\right]^{0.125} \tag{51}$$

$$\begin{aligned}(Q_{\ell_i}')^{n+1} = {} & (Q_{\ell_i}')^n - w_i^n \frac{\Delta t}{\Delta Z}(Q_{\ell_{i+1}}' - Q_{\ell_i}')^n + \frac{w_i^n \Delta t}{(V+w)_i^n} \Bigg\{ (-Q_{\ell_i}')^n \left[\frac{V_i (\ln \rho_{i+1} - \ln \rho_i) + (V_{i+1} - V_i)}{\Delta Z}\right]^n \\ & - \mu_i^n w_i^n (Q_{\ell_i}')^n + k_1 \left[(Q_{c_i}')^n - \frac{a}{\rho_i^n}\right] + k_2 \left[\left(\frac{\rho_0}{\rho_i}\right)^n\right]^{\frac{1}{2}} (\rho_i^n)^{7/8} (Q_{c_i}')^n \left[(Q_{\ell_i}')^n\right]^{7/8} \Bigg\}\end{aligned} \tag{52}$$

$$w_i^{n+1} = w_i^n - \frac{w_i^n(w_{i+1}^n - w_i^n)}{\Delta Z} - \mu_i^n (w_i^n)^2 \Delta t$$

$$+ \Delta t \left[\frac{(1+0.61 q_{si}^n) T_i^n - (1+0.61 q_{ei}) T_{ei}}{(1+0.61 q_{ei}) T_{ei}} - (Q_{c_i}' + Q_{h_i}')^n \right] \quad (53)$$

$$r_i^{n+1} = r_i^n - \frac{w_i^n \Delta t (r_{i+1}^n - r_i^n)}{\Delta Z} + 9 \Delta t\, w_i^n - \frac{w_i^n r_i^n \Delta t}{2} \left[\frac{\ln w_{i+1}^n - \ln w_i^n}{\Delta Z} + \frac{\ln(\rho_{i+1}^n) - \ln \rho_i^n}{\Delta Z} \right] \quad (54)$$

Procedure for Solving System

Given: $\alpha_1, A_1, g, c_p, J, R, \epsilon, k_1, a, k_-, \rho_B, K_3$ are constants

$K_3 = 15.39$ before ice nucleation

$K_3 = 11.58$ after nucleation

$L = 595$ cal gm^{-1}, $T > 273°K$, $L_s = L_f = 0$

$$L = \begin{cases} L_s = 677 \text{ cal } gm^{-1} \\ L_f = 80 \text{ cal } gm^{-1} \end{cases} \quad T \leq 273°K$$

Initial Data: T_{ei}, q_{ei}, T_i^o, $(Q_{ci}')^o$, $(Q_{hi}')^o$.

Boundary Data Given: T_B^n, ρ_B^n, w_B^n, r_B^n, $(Q_c')_B^n$, $(Q_h')_B^n$, P_B^n.

1) Calculate $\overset{o}{q}_{si}$ from Equation (40) or (41).

2) Calculate $(w_{i+1}^2)^o$ from Equation (43). Use $w = w_R$ at $Z = Z_B$.

3) Solve for w_{i+1}^o.

4) Calculate $\overset{o}{r}_{i+1}$ from Equation 44). Use $r = r_B$ at $Z = Z_B$, w_{i+1}^o and w_i^o are known from Step 3. ρ_{i+1}^o and ρ_i^o are calculated from Equation (45) and (46). Stop calculation at level where $w = 0$.

5) Solve for μ_i from Equation (47).

5) Calculate $\frac{T_i^{n+1} - T_i^n}{\Delta t} + w_i^n \frac{(T_{i+1}^n - T_i^n)}{\Delta Z}$ from Equation (48).

7) Solve Equation (49) for T_i^{n+1}. If $T_i^n \leq 273°K$, include $L_S(Q'_{c_i} + Q'_{R_i})^n$ and $(\Delta q_{s_i})^n$ water ⟶ ice. Let $L = L_S$ at that level and all levels above.

8) If $T_i^n \leq 273°K$, return to Step 6 and recalculate

$$\frac{T_i^{n+1} - T_i^n}{\Delta t} + w_i^n \frac{(T_{i+1}^n - T_i^n)}{\Delta z}$$

including freezing terms.

9) Solve Equation (50) for $(Q'_{c_i})^{n+1}$. Include the term

$$k_1 \left[(Q'_{c_i})^n - \frac{a}{\rho_i^n} \right] \text{ if } (Q'_{c_i})^n > \frac{a}{\rho_i^n}.$$

If $(Q'_{c_i})^n < \frac{a}{\rho_i^n}$, omit this term.

In either case, include

$$k_2 \left[\left(\frac{\rho_B}{\rho_i}\right)^n \right]^{\frac{1}{2}} (\rho_i^n)^{7/8} (Q'_{c_i})^n \left[(Q'_{R_i})^n \right]^{7/8}.$$

10) Solve for V_i^n from Equation (51).
If $T > 273°K$, $K_3 = 15.39$.

If $T \leq 273°K$, $K_3 = 11.58$.

11) Solve Equation (52) for $(Q'_{R_i})^n$.

12) Solve Equation (53) for w_i^{n+1}.

13) Solve Equation (54) R_i^{n+1}.

14) Return to Step 1, but now $(Q'_{c_i})^1$ and $(Q'_{R_i})^1$ may not be zero.

15) Skip Steps 2, 3, 4, and go to Step 5.

16) Continue the procedure through Step 13.

17) Go to Step 14, and update everything by 1. Stop all calculations at time $n+1$ at the level where $w_i^{n+1} = 0$.

<u>Experiments</u>

We have run eight experiments, with five sets of initial data. With each set of initial data, two runs were made - one with variable Δt, one with constant Δt. The variable Δt was determined from

$$\Delta t \leq \frac{\Delta z}{w} \tag{55}$$

at each time step. In each case, probably due to choice of initial conditions, the cloud life was short. In an effort to determine whether this brevity was related to the numerical aspects, we ran each case with several time steps, each one constant throughout the run. We selected the time step which gave the longest life cycle for comparison of results using variable Δt. We used $\Delta z = 200$ m.

In all but two cases, we have chosen as boundary data $w = 1$ m sec^{-1}, $r = 1$ km, $Q_c = Q_h = 0$ at base of cloud. We used $\alpha = 0.15$ in the entrainment equation. The initial data have been varied in each experiment. The top of the cloud is that level at which $w = 0$.

Case 1: In an earlier paper (Berkofsky, 1974), we have solved the steady-state equations. We used the results of that experiment as input data for T_i, T_e, Q_c, Q_h. Fig. 1 shows the temperature profiles within the "cloud" at $t = 0$, 21, 140, 264 seconds, for variable Δt. The ordinate is temperature, T, the abscissa the number of the level, L. By time 264 seconds, there are only 4 levels left. At the same time (Fig. 2), the cloud radius at the top has decreased from about 1.84 km at the top to .79 km at the top. The vertical velocity (Fig. 3) at the last non-zero level has decreased from 5.55 m sec^{-1} to 1.87 m sec^{-1}. The cloud water (Fig. 4) has actually increased at the top level at 264 seconds, but (Fig. 5) the hydrometeor water has decreased substantially. Notice that the patterns of r, w and Q_c appear to oscillate widly at $t = 140$ seconds, but then settle down as the cloud dissipates.

We ran this case with w at base = 105 cm sec., with similar results.

Case 2: This is a repeat of Case 1, but with $\Delta t = 9$ seconds - constant. The cloud lasts longer (until 7 minutes). The results, Fig. 6-10, for 9, 90, and 315 seconds are plotted. These are similar to Case 1, but do not oscillate as wildly. The increase in stability within the cloud, plus the decrease of vertical velocity at the top, lead to its destruction, despite the increase in cloud water.

Case 3: We have used real data from Sede Boqer, 2 March 1982, at 1322. The environmental temperature profile, T_E, is the same as the curve labelled Initial in Fig. 11, except that the lowest five levels have been given a temperature increase in order to provide a perturbation for development. This perturbation was calculated from

$$T' = 1 + \cos\left[\frac{\pi(K-2)}{4}\right] \tag{56}$$

where K = 1, 2, 3, 4, 5, (See Hill, 1974).

With variable Δt, the cloud "disappeared" after 3 minutes. The results for 18 and 145 seconds are shown. At that time, the "cloud" was still 4400 m thick. At the time the data were taken (1322 LST), there was a cloud cover of 6/8 cumulus congestus. But the lapse rate in the lower layers become very stable, leading to the cloud's disappearance. Nevertheless, the cloud radius, the vertical velocity, the liquid water, and hydrometeor water all reached maximum values within the cloud at about 2800 m before dissipating (see Figs. 11-15 inclusive). In actual fact, the cloudiness persisted until evening. This is not predicted by the model.

Case 4: Same as Case 3, but with $\Delta t = 7$ seconds = constant. In this case, the cloud lasted for 3.5 minutes. The results are shown for 7 seconds, 20 seconds, 140 seconds, 245 seconds, (see Fig. 16-20 inclusive). The results are very similar to those for variable Δt (Case 3), except they are slightly more stable.

Case 5: We have used real data for 10 March 1982 for Sede Boqer, at 1257. The calculations showed the cloud dissipating after about 4.5 minutes. The results for 20, 126, and 189 seconds are plotted on Figs. 21-25 inclusive. Even though the cloud had expanded at the top, and the vertical velocity and liquid water increased, the lapse rate was so stable that the cloud could not grow. In actual fact, cloudiness of 7/8 stratocumulus persisted throughout the day, with occasional light rain. One of the problems here is that the radiosonde went through the clouds, giving cloud temperature instead of environmental temperature.

Case 6: Same as Case 5, but with $\Delta t = 9$ seconds = constant. Figs. 26-30 inclusive summarize the results. The main difference between this run and that for variable Δt is that the cloud lasted about 2 minutes longer, and the hydrometeor water stayed higher for a longer time.

Case 7: We have used real data from Sede Boqer, 17 March 1982, at 1300. There was a cloud cover of 6/8 stratocumulus, which disappeared later in the day, With variable Δt, the cloud disappeared after 3.5 minutes. The plots Figs. 31-35 inclusive, show results at t = 20, 124 seconds. Actually, at 124 seconds, the clouds top was still at 11,200 m, but dropped to zero in another 1.5 minutes. In the actual atmosphere, the clouds dissipated during the afternoon, but it is not known exactly when. Notice that in the calculations, the radius of the top had increased considerably by t = 124 seconds, the overall vertical velocity had increased, as did the top cloud water content. But the hydrometeor water increased only in the first few hundred meters above the base, where the cloud radius was smallest and where the cloud lapse rate had become very stable.

Case 8: Same as Case 7, but with $\Delta t = 9$ seconds = constant. The cloud lasts for 414 seconds, instead of 205 seconds. However, the collapse of the cloud took place at an early stage, the cloud top dropping to 4,000 m by 135 sec. This is probably more realistic than with variable Δt, since it is unlikely that the cloud tops grew to 11,200 m in the atmosphere. The results are shown in Figs. 36-40, inclusive.

Inclusion of Cloud Model In A Model of Larger-Scale Flow

In an earlier paper (Berkofsky, 1974), we have described how a cloud model might be included in one for the larger-scale. In essence, we solve three systems of equations: one for the sub-cloud layer, one for the free air, one for the cloud. In the operational scheme, we actually assume the existence of a cloud within each grid rectangle. The modality of the ensemble is to be prescribed from observations. Thus in the Central Pacific, the cloud distribution is bimodal. Whenever the equations for the larger-scale, free air, predict at least a conditionally unstable lapse rate, it is assumed that a cloud ensemble exists at that grid point. The cloud equations are then solved, using input data from the free air model, and assumed radii of bases. The condensation heating term in the first law of thermodynamics is calculated from

$$\frac{L}{c_p}\frac{\Delta \overline{Q'_{c_i}}}{\Delta t} = \frac{L}{c_p}\frac{\Delta}{\Delta t}\sum_{i=1}^{I} f_i\, Q'_{c_i} \qquad (57)$$

where the bar is a horizontal average over a grid spacing, Δt is the time step for the larger-scale motions, f_i is the fraction of sky covered by the ith population of convective clouds. Here Q_{c_i} is the cloud liquid water, which is calculated by the cloud model. The quantity $\frac{\Delta \overline{Q'_{c_i}}}{\Delta t}$ is calculated from

$$\frac{\Delta \overline{Q'_{c_i}}}{\Delta t} \approx \frac{\overline{Q'_{c_i}}(t+\Delta t) - \overline{Q'_{c_i}}(t)}{\Delta t} \qquad (58)$$

in which we assume

$$\frac{\Delta \; Q'_{c_i}(t=0)}{\Delta t} = 0 \; . \tag{59}$$

This quantity represents the rate of change of condensed water by the clouds. This together with the cloud heating, is fed into the larger-scale equations, thus influencing the entire surrounding circulation, and hence the moisture supply for subsequent cloud calculations.

Complete details of the model and the procedure for solving the system are given in Berkofsky (1974). The cloud model in that paper differs in some minor details from the present one.

Conclusions

We have developed a one-dimensional time dependent "plume" model to predict the growth of a cumulus cloud. In all of the cases we studied, using both real and artificial data, the "cloud" had a short life-time-of the order of several minutes. This may be due to our choice of initial conditions. It is possible that, had we varied the initial temperature perturbation, the initial vertical velocity at cloud base, the initial cloud radius, development would have been otherwise. Our choice of a cloud radius and a vertical velocity at base implies that a cloud exists. What is more likely is that the temperature difference between our developing "cloud" and the real atmosphere was such as to perclude any further development.

During the entire course of the numerical experimentation, we never reached the point where we had sufficient observations, both in the ambient atmosphere and of the actual cloud growth, to test the predictions. Even on days when there were clouds, there were no continuous cloud observations, so it is not certain whether a specific cloud, predicted to decay, actually did so.

Nevertheless, it is felt that the model deserves further testing. In the very near future, we will be in a much better position to measure required data as input and verification of the model. These will include radar data.

Recommendations

It is recommended that the model be re-tested when more data become available in the Negev. It is possible that such data exist in U.S. deserts.

It is also recommended that the model be used in conjunction with a larger-scale model. Thus, when the larger-scale model predicts that the air at a grid-point is at or near saturation, that the lapse rate is conditionally unstable, that the vertical velocity of the larger-scale motion is upward, it is assumed that an ensemble of clouds exist. The modality and the input data (radius of base, vertical velocity of base, cloud water and liquid water at base) will be assumed from known cloud statistics of the region, and will be used as input data, together with ambient temperature from the larger-scale model, to solve the cloud equations. The total latent heat released at each grid point is then calculated from Eq. (58), and fed into the first law of thermodynamics for the larger-scale motions.

Finally, it is recommended that the model be modified to include a dust equation. As a first attempt, we might consider a dry atmosphere, lacking either cloud water or hydrometeor water, in which dust is entrained during conditionally unstable conditions. It would be of great interest to calculate the height to which a dust cloud, emanating from the ground, would grow. Even a steady-state calculation would be revealing.

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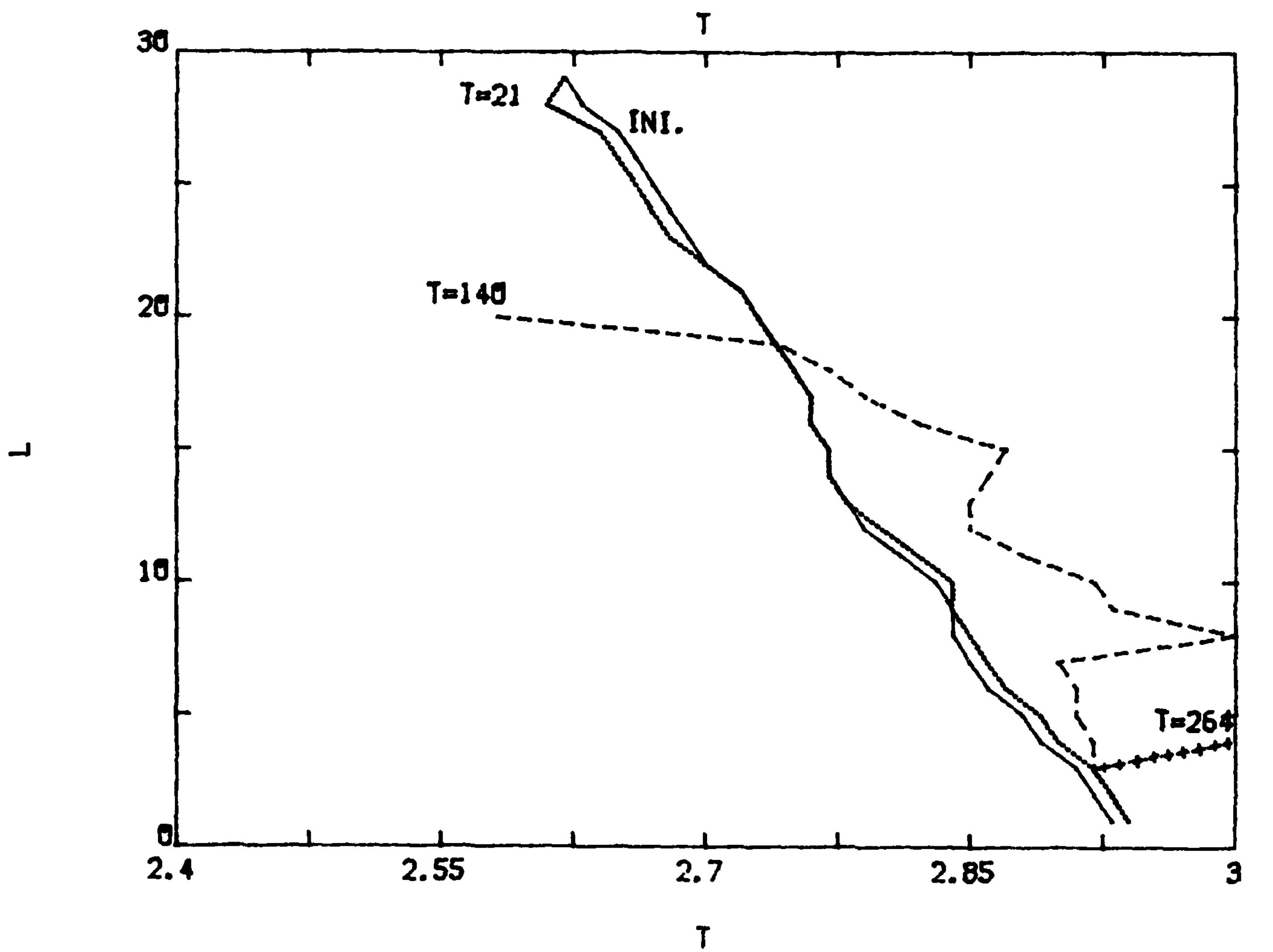

Fig. 1. Cloud Temperature x 10^{-2} (Degrees k) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 1.

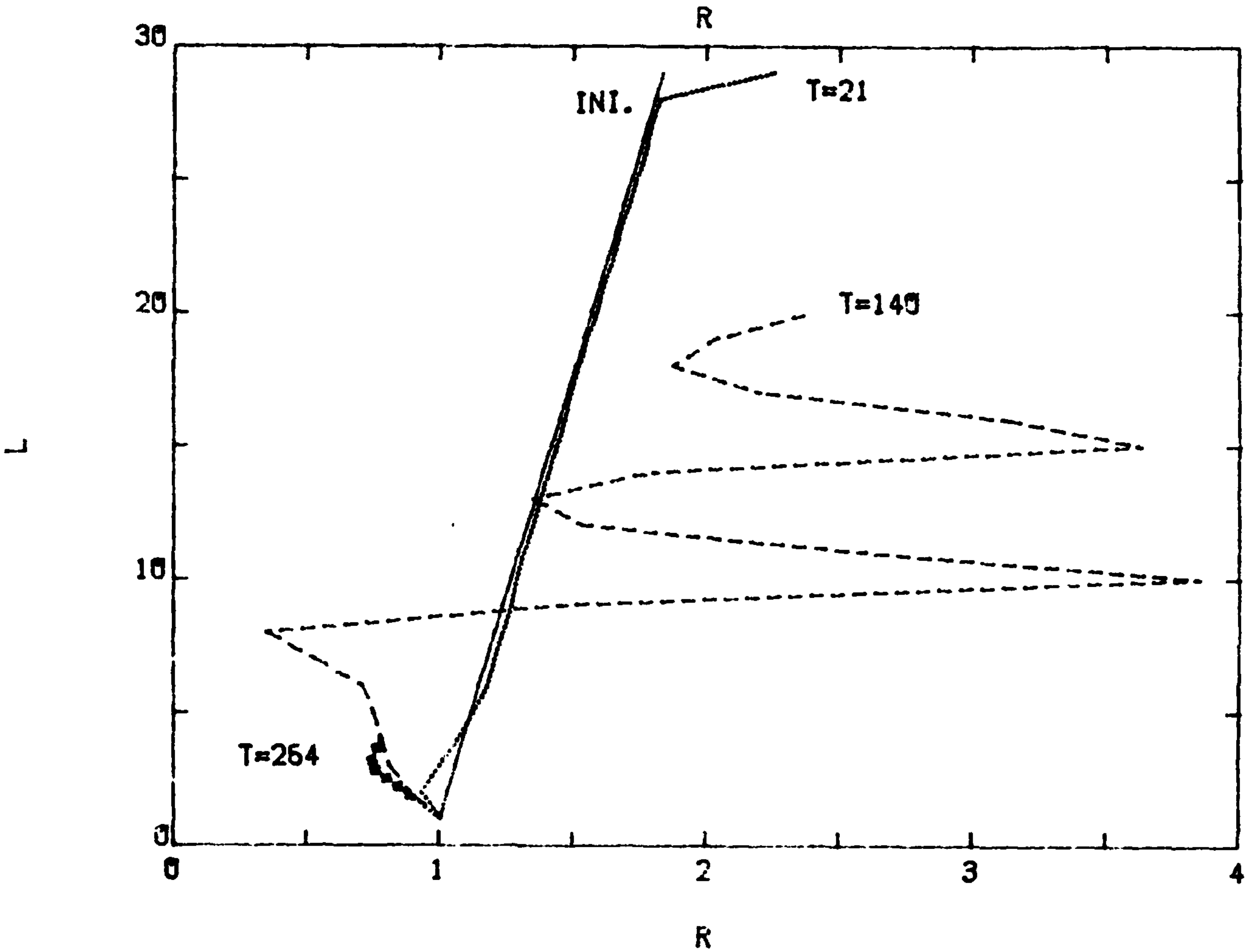

Fig. 2. Cloud Radius x 10^{-5} (cm) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 1.

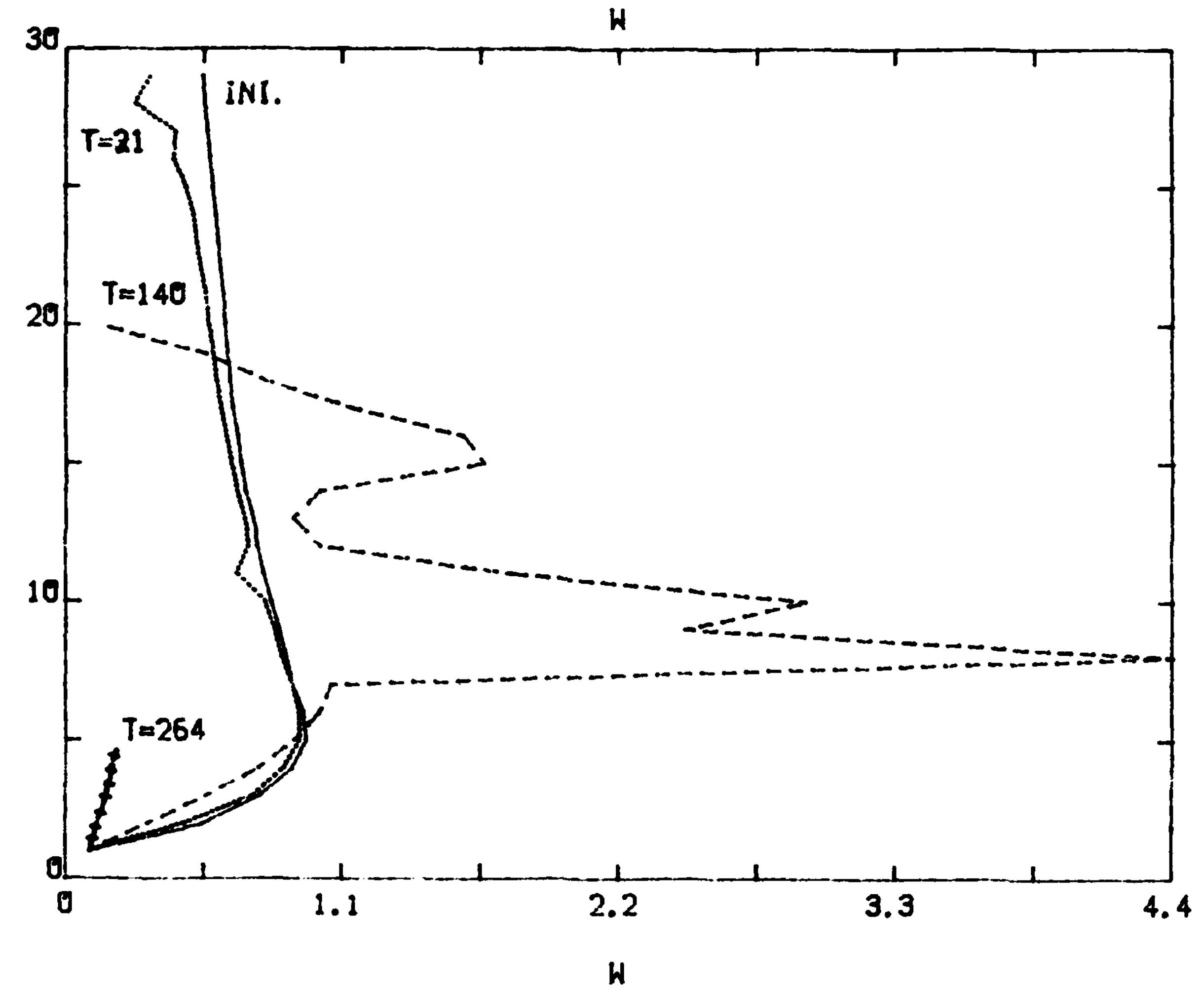

Fig. 3. Vertical Velocity x 10^{-2} (cm sec^{-1}) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 1.

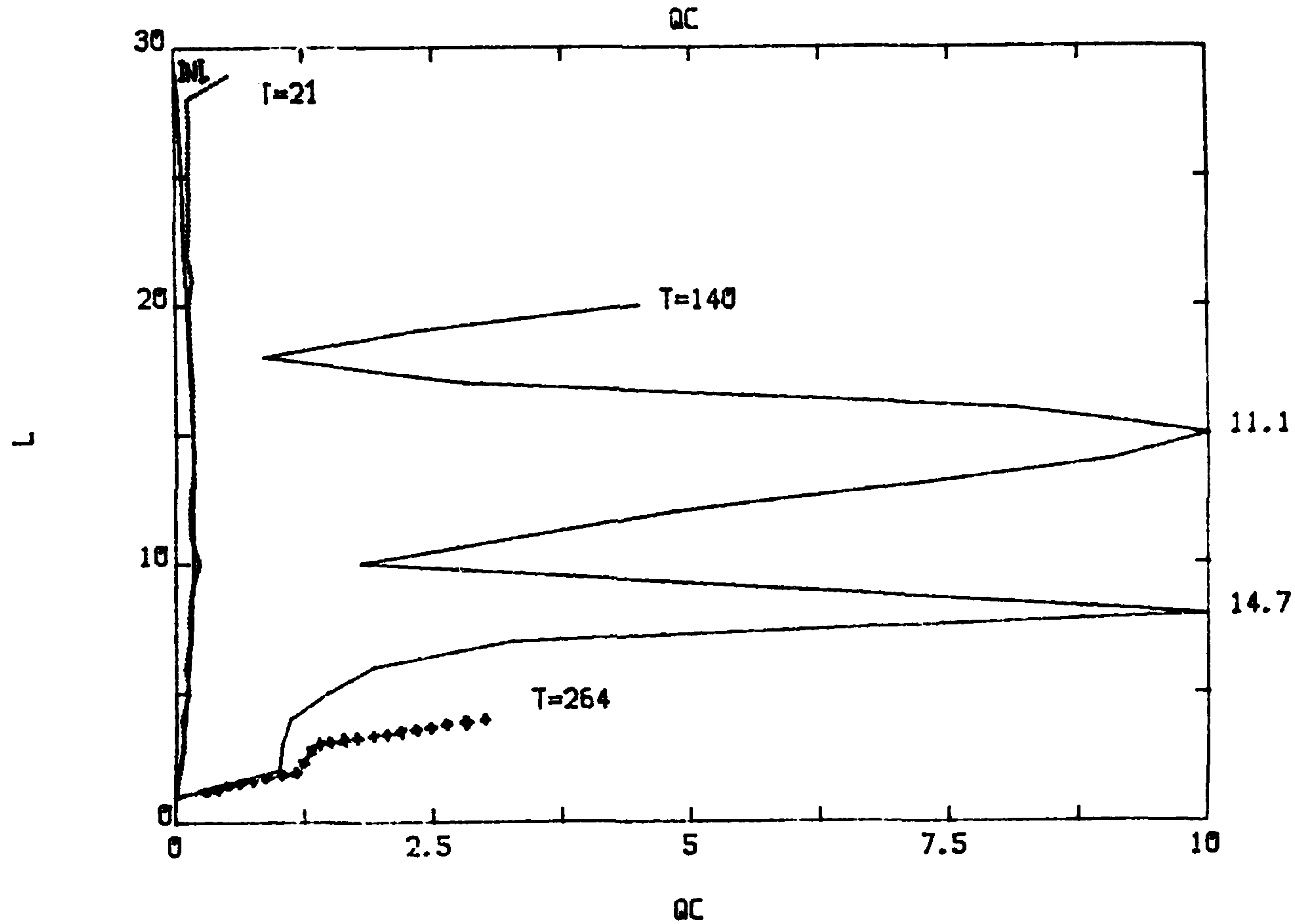

Fig. 4. Cloud Water Content x 10^2 (gmgm-1) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 1.

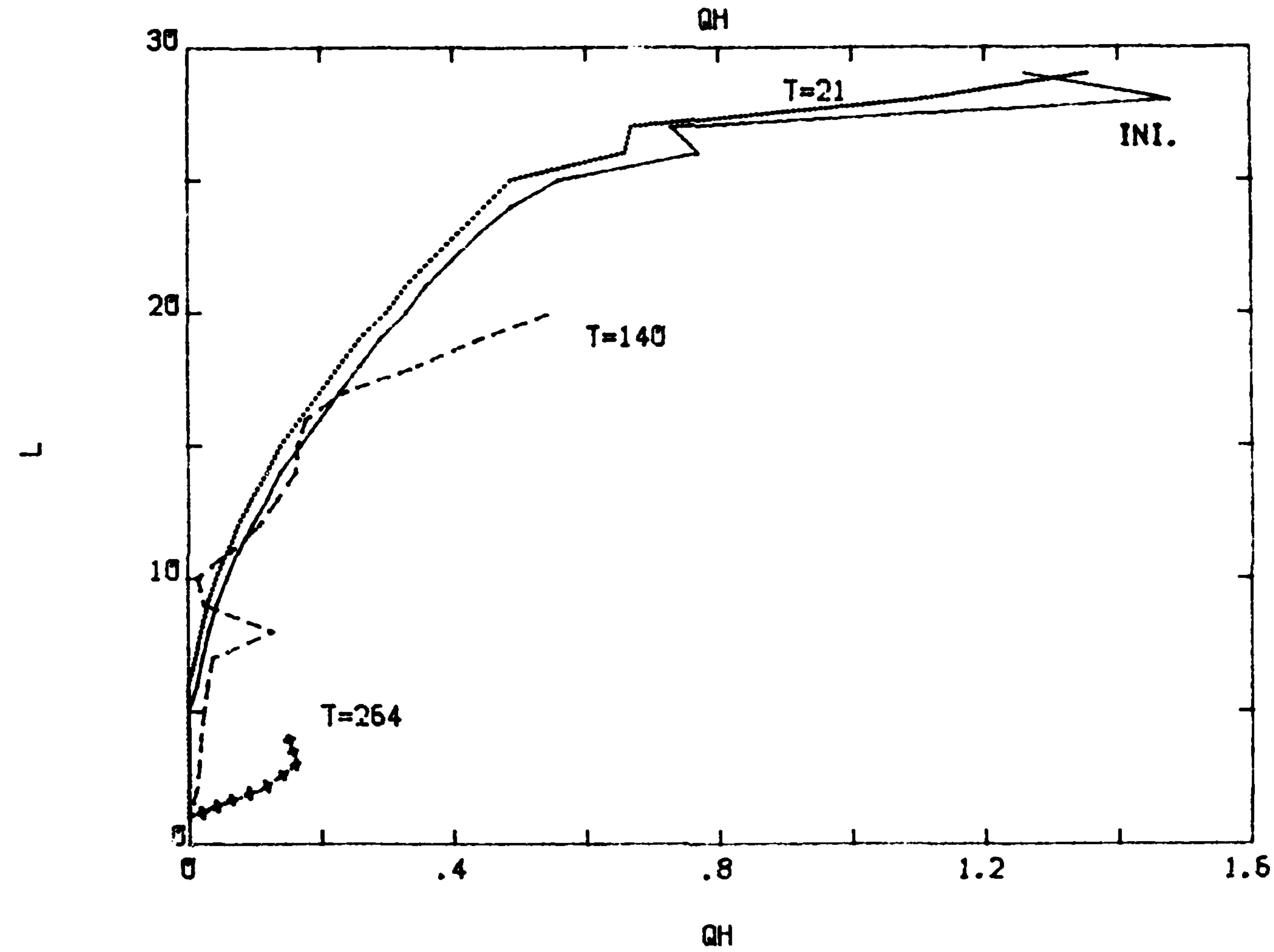

Fig. 5. Hydrometeor Water Content x 10^2 ($gmgm^{-1}$) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 1.

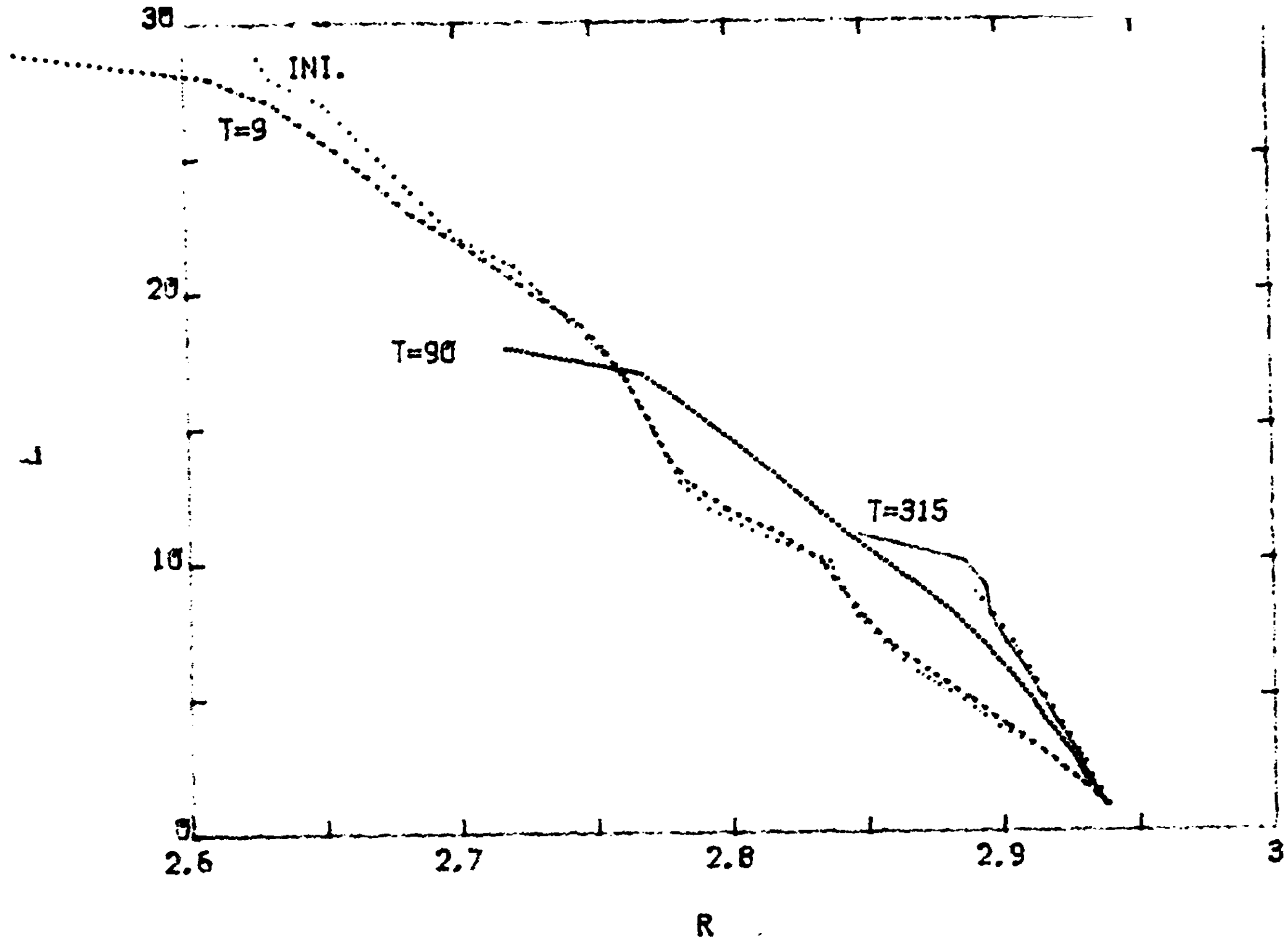

Fig. 6. Cloud Temperature $\times 10^{-2}$ (Degrees k) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 2.

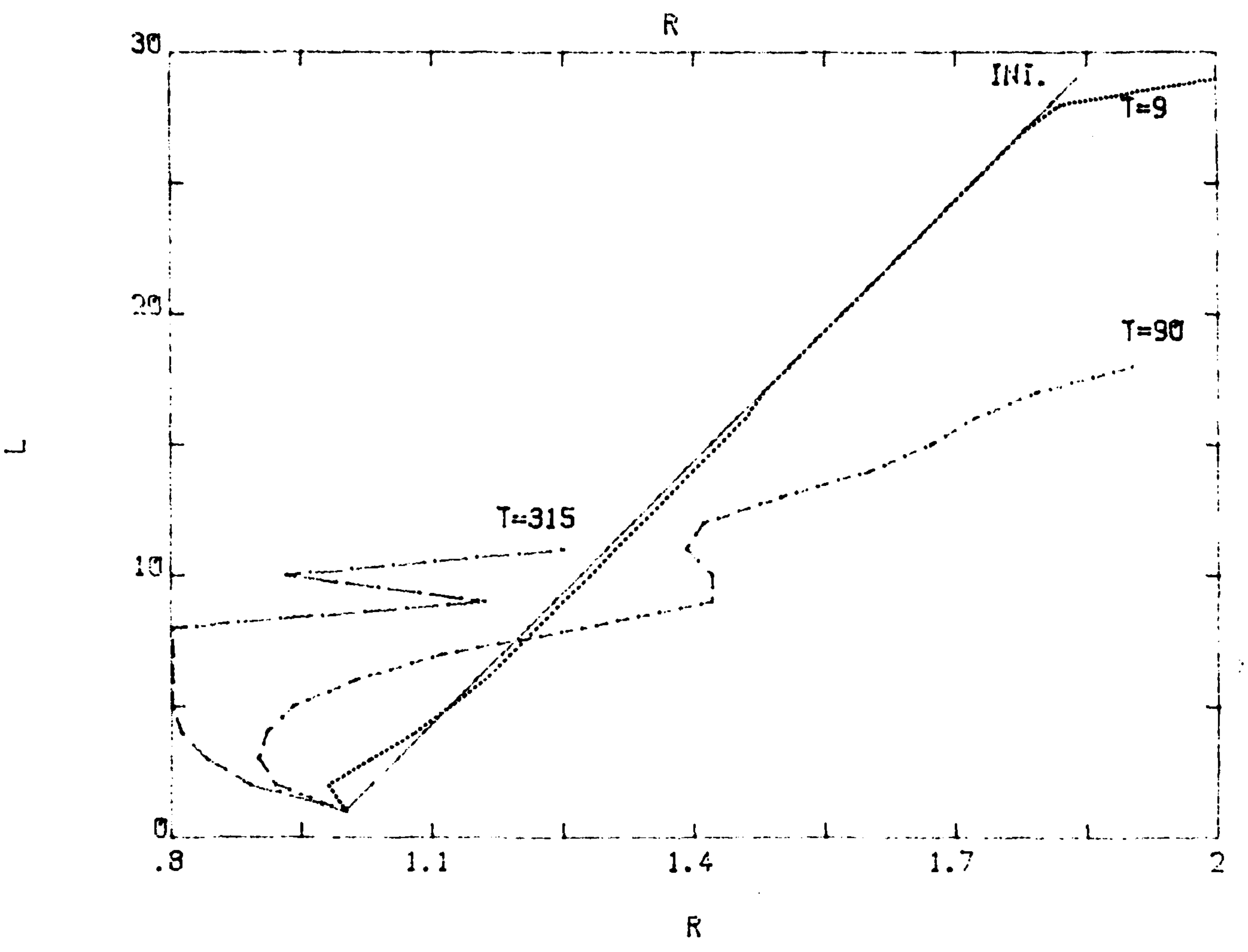

Fig. 7. Cloud Radius $x10^{-5}$ (cm) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 2.

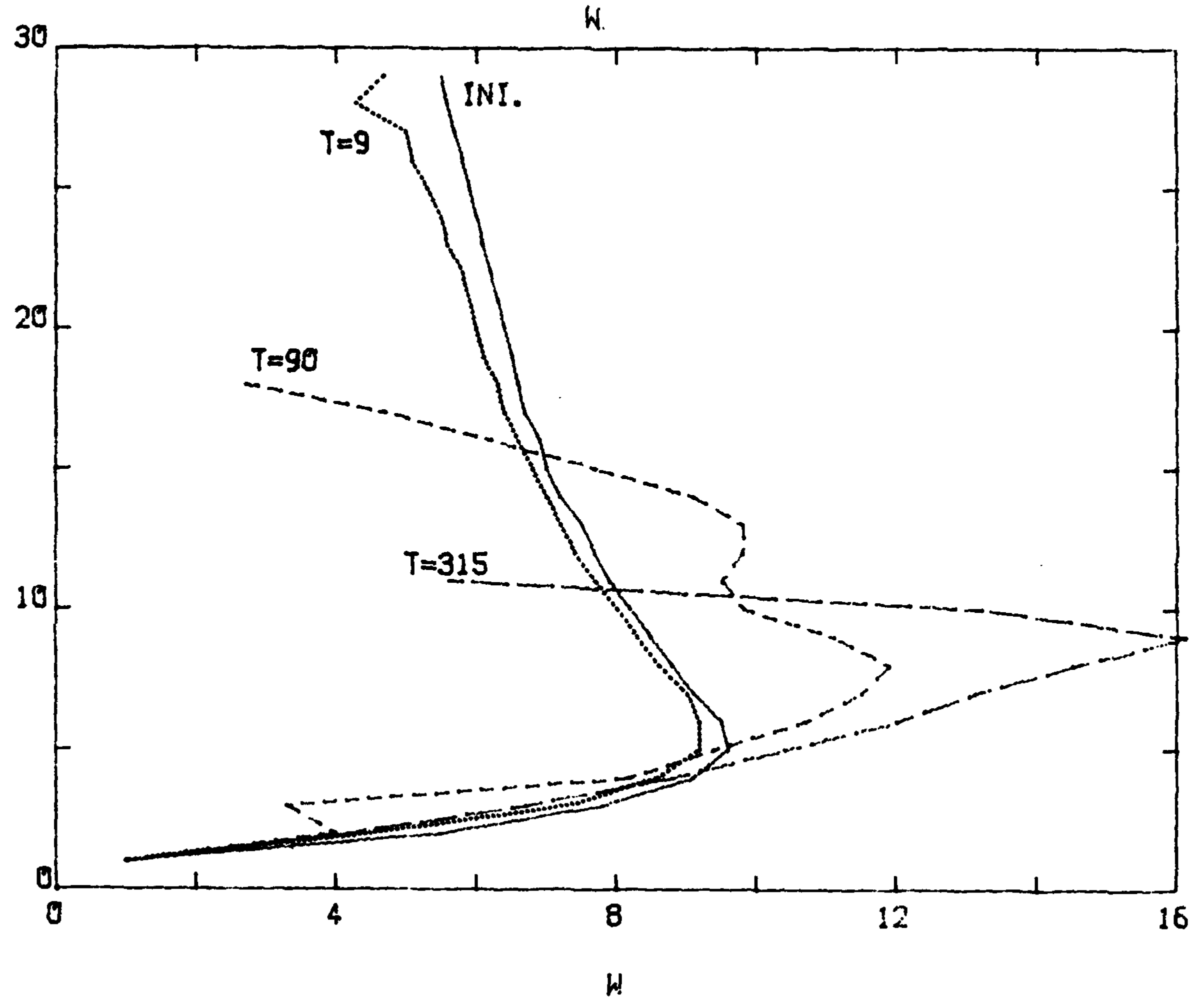

Fig. 8. Vertical Velocity $\times 10^{-2}$ (cm sec^{-1}) vs. Level Number (Vertical Resolution is 200 *m*) as a Function of Time (seconds), Case 2.

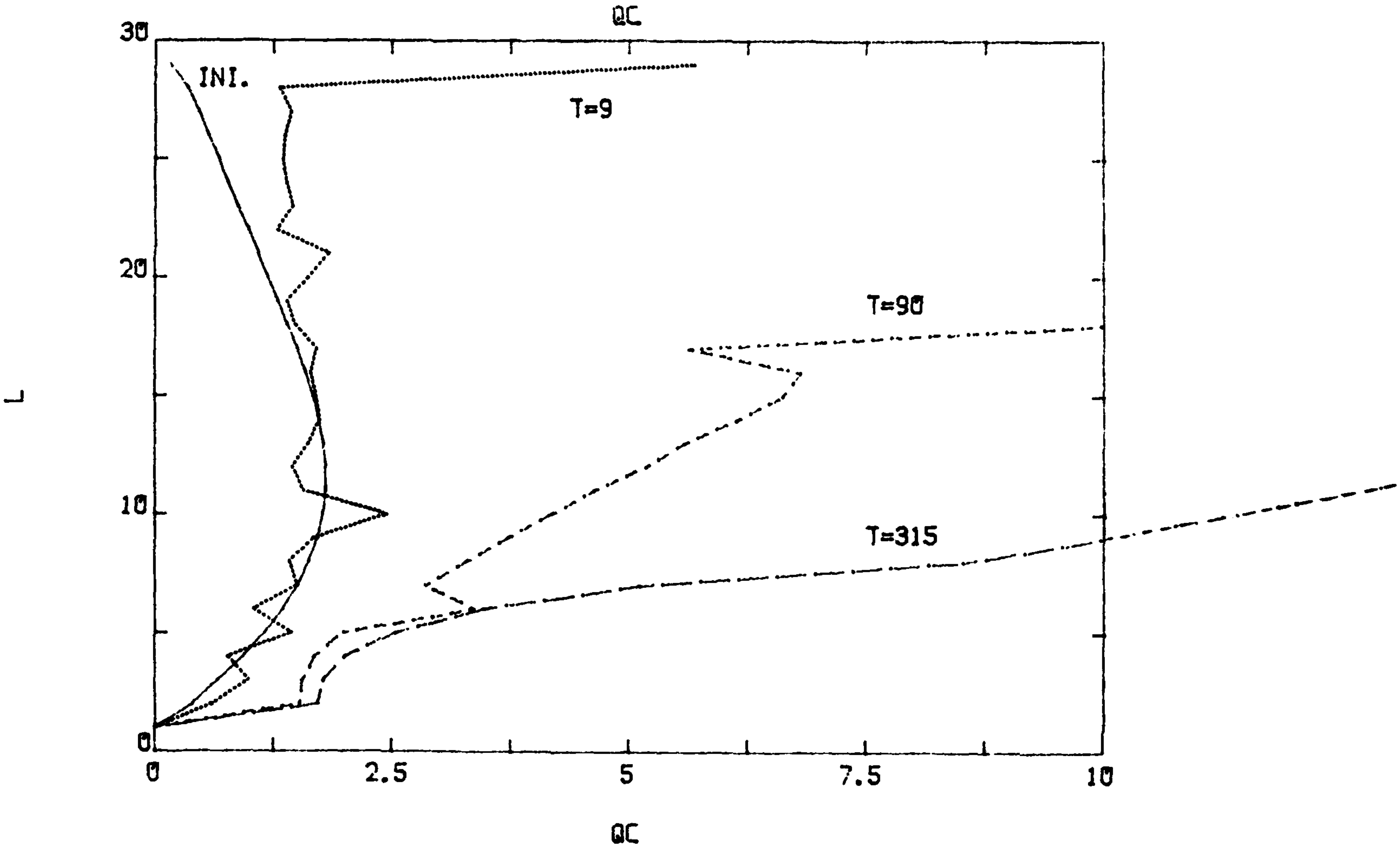

Fig. 9. Cloud Water Content x10 ($gmgm^{-1}$) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 2.

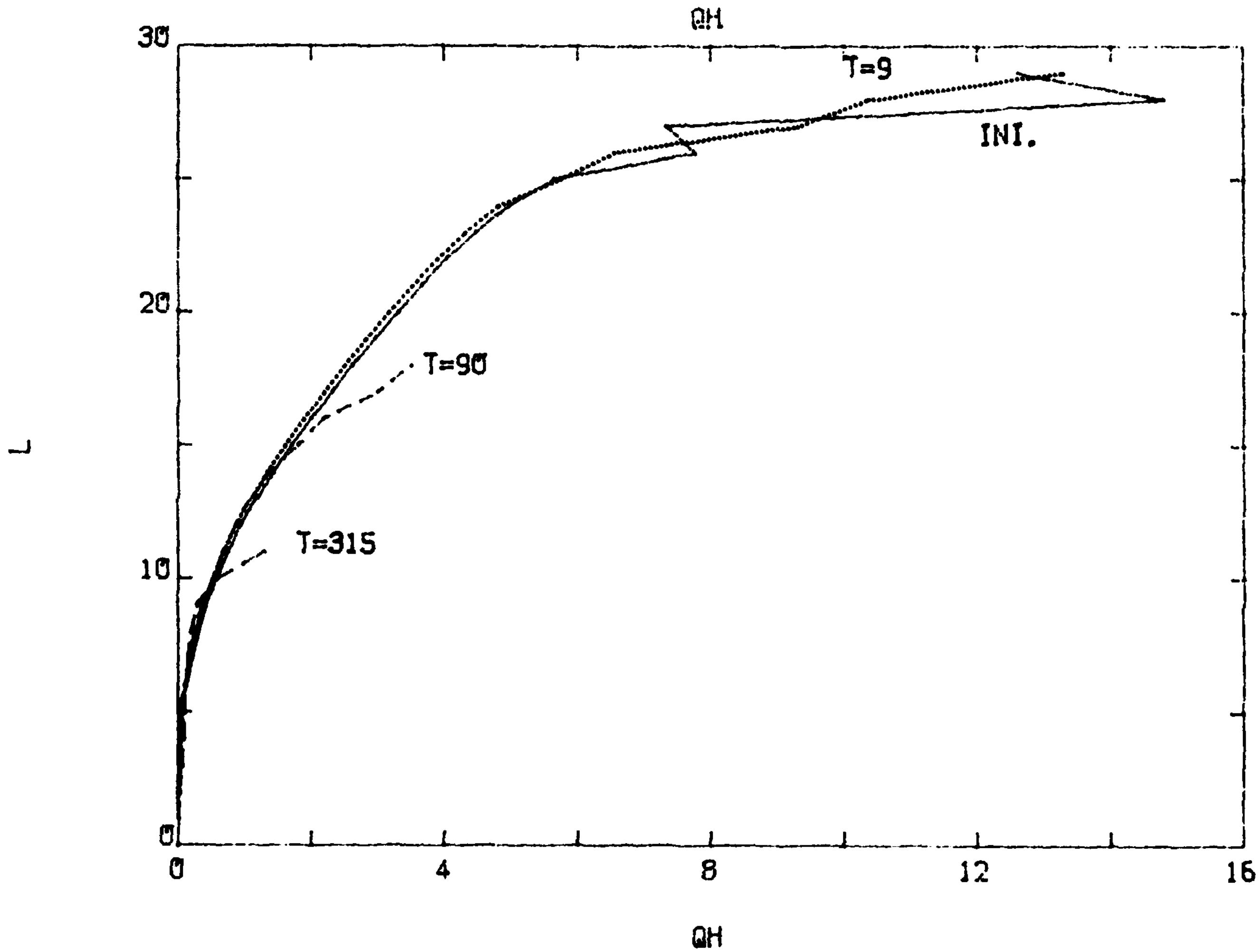

Fig. 10. Hydrometeor Water Content x10^2 ($gmgm^{-1}$) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 2.

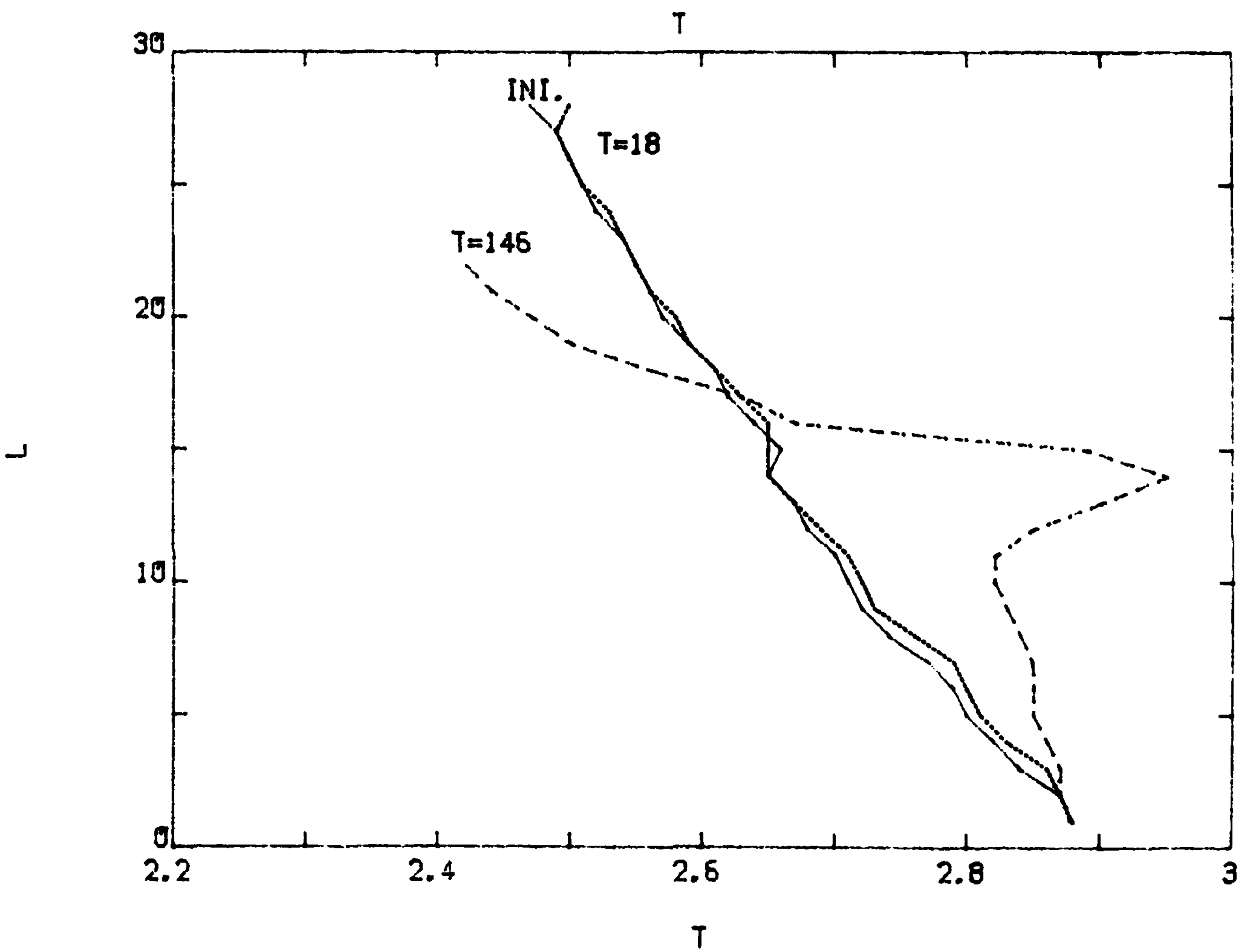

Fig. 11. Cloud Temperature x10^{-2} (Degrees K) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 3.

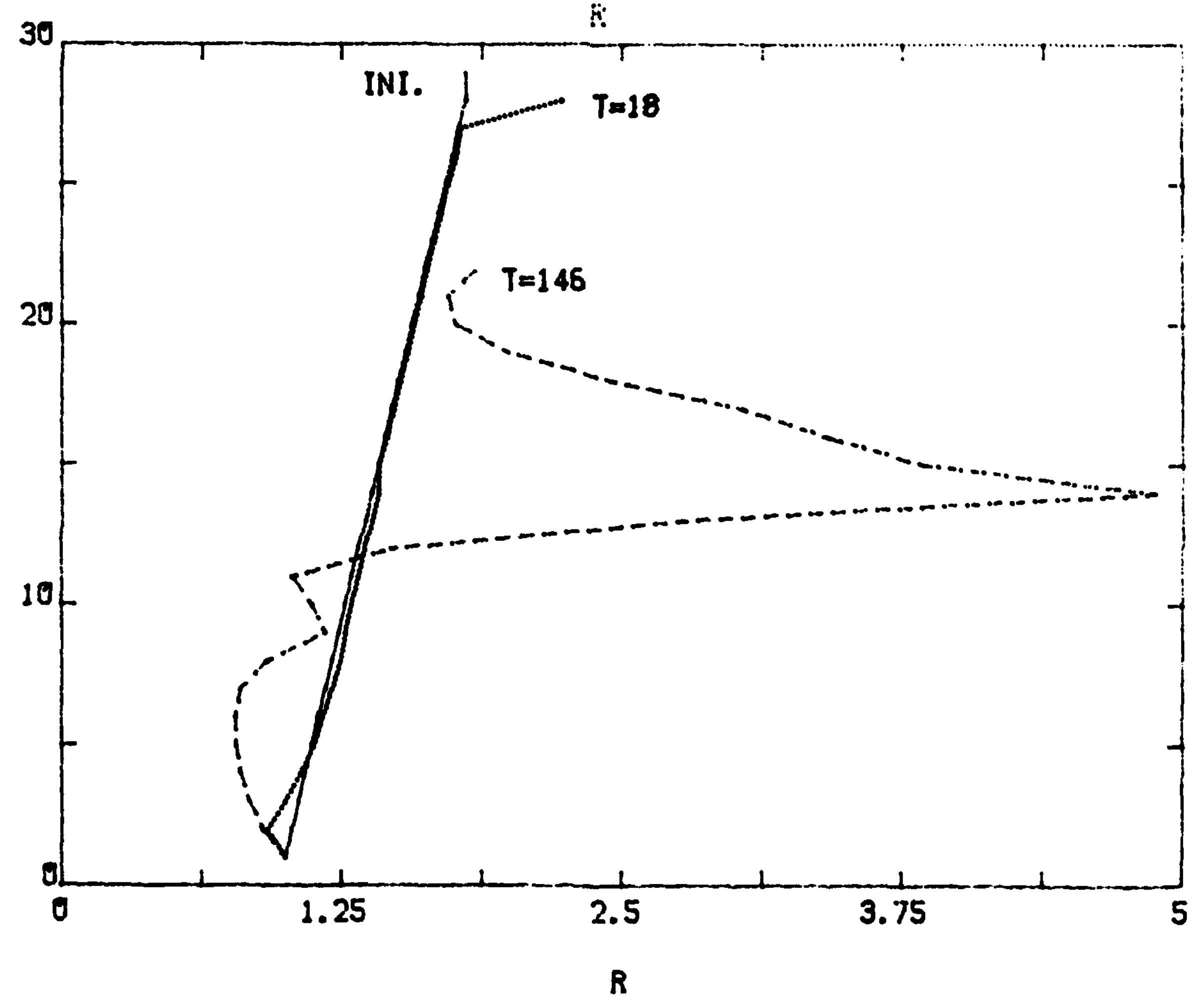

Fig. 12. Cloud Radius x10^{-5} (cm) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 3.

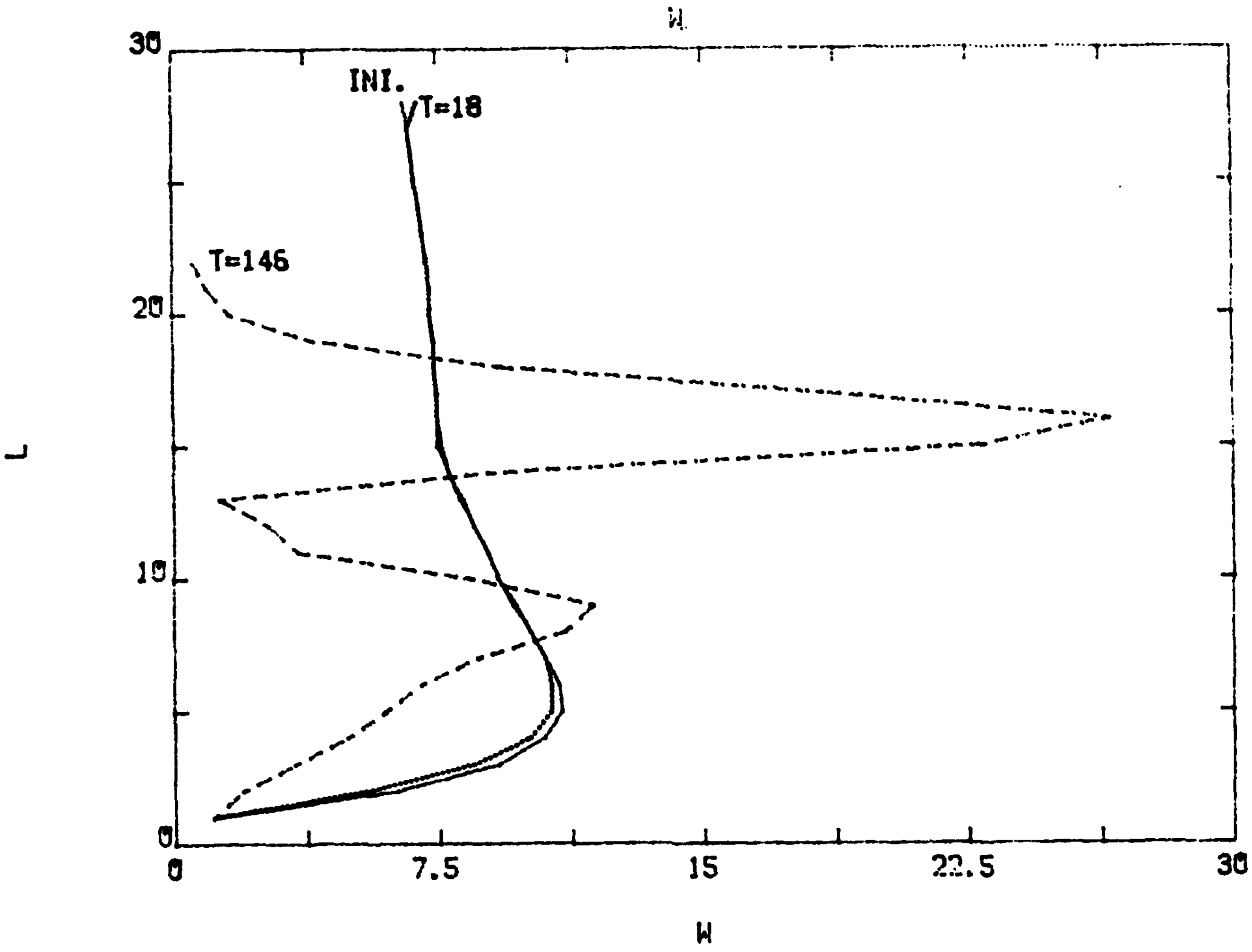

Fig. 13. Vertical Velocity $x10^{-2}$ (cm sec^{-1}) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 3.

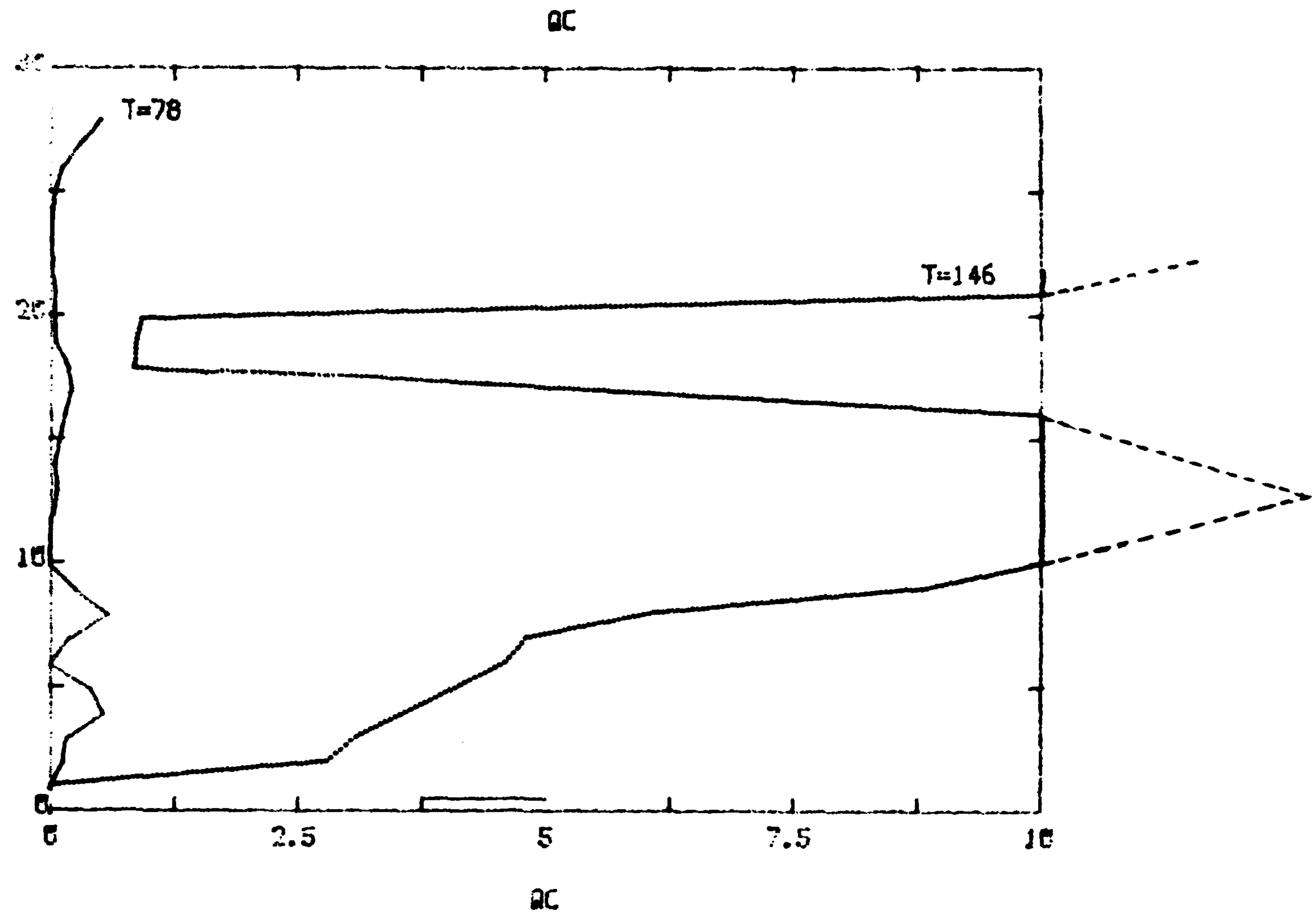

Fig. 14. Cloud Water Content $x10^2$ ($gmgm^{-1}$) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 3.

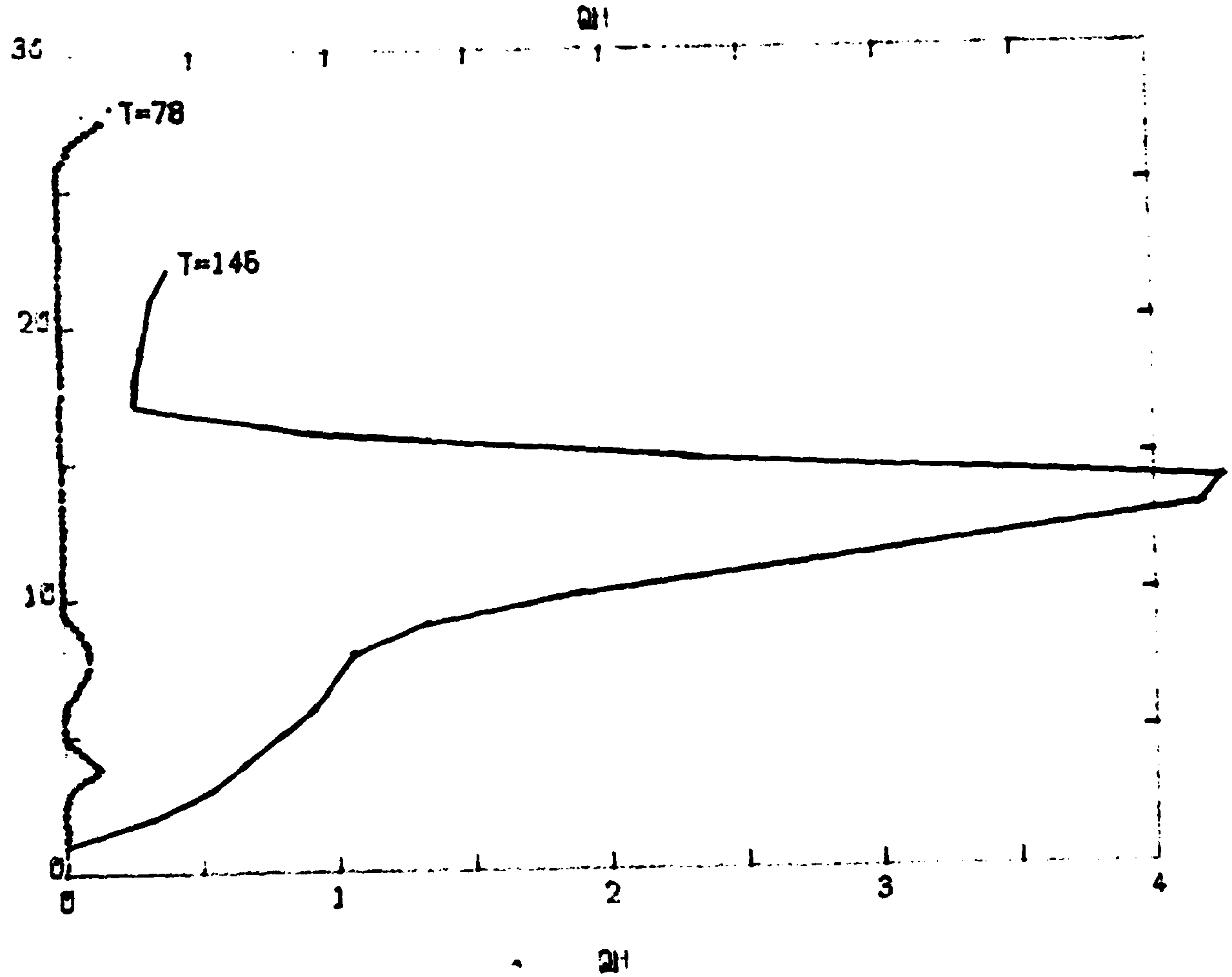

Fig. 15. Hydrometeor Water Content x10^2 ($gmgm^{-1}$) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds) Case 3.

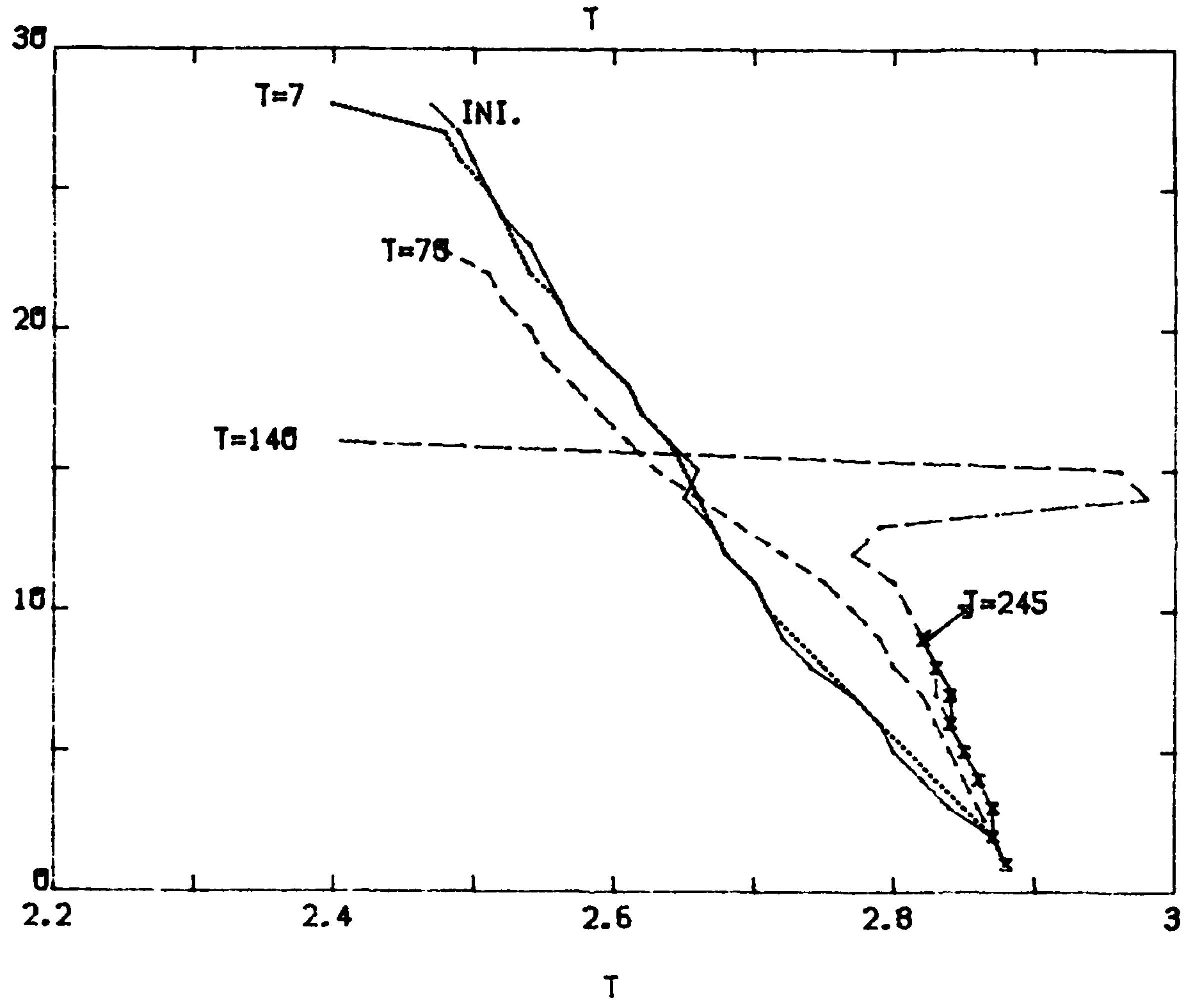

Fig. 16. Cloud Temperature x10^{-2} (Degrees K) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 4.

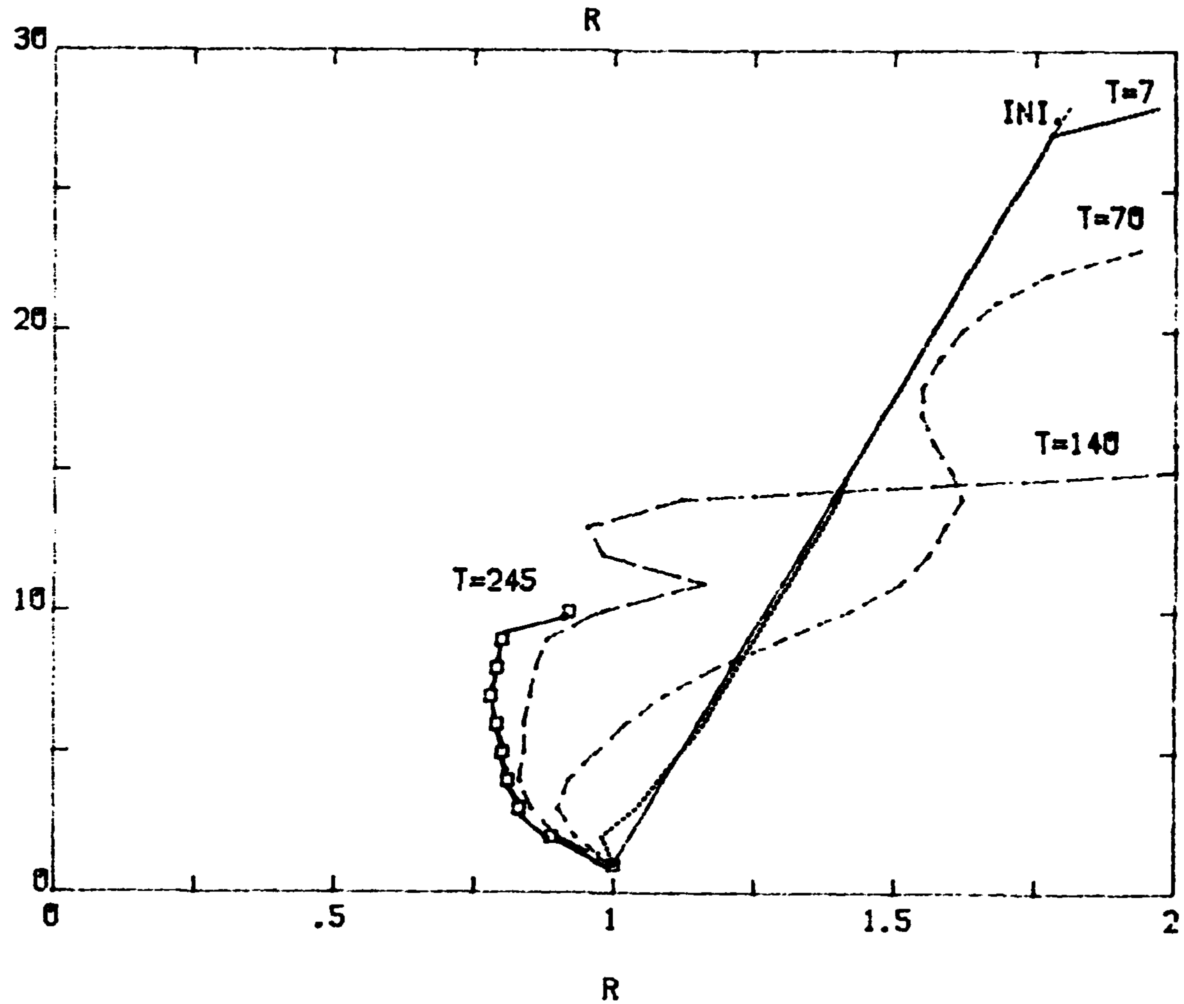

Fig. 17. Cloud Radius x10^{-5} (cm) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 4.

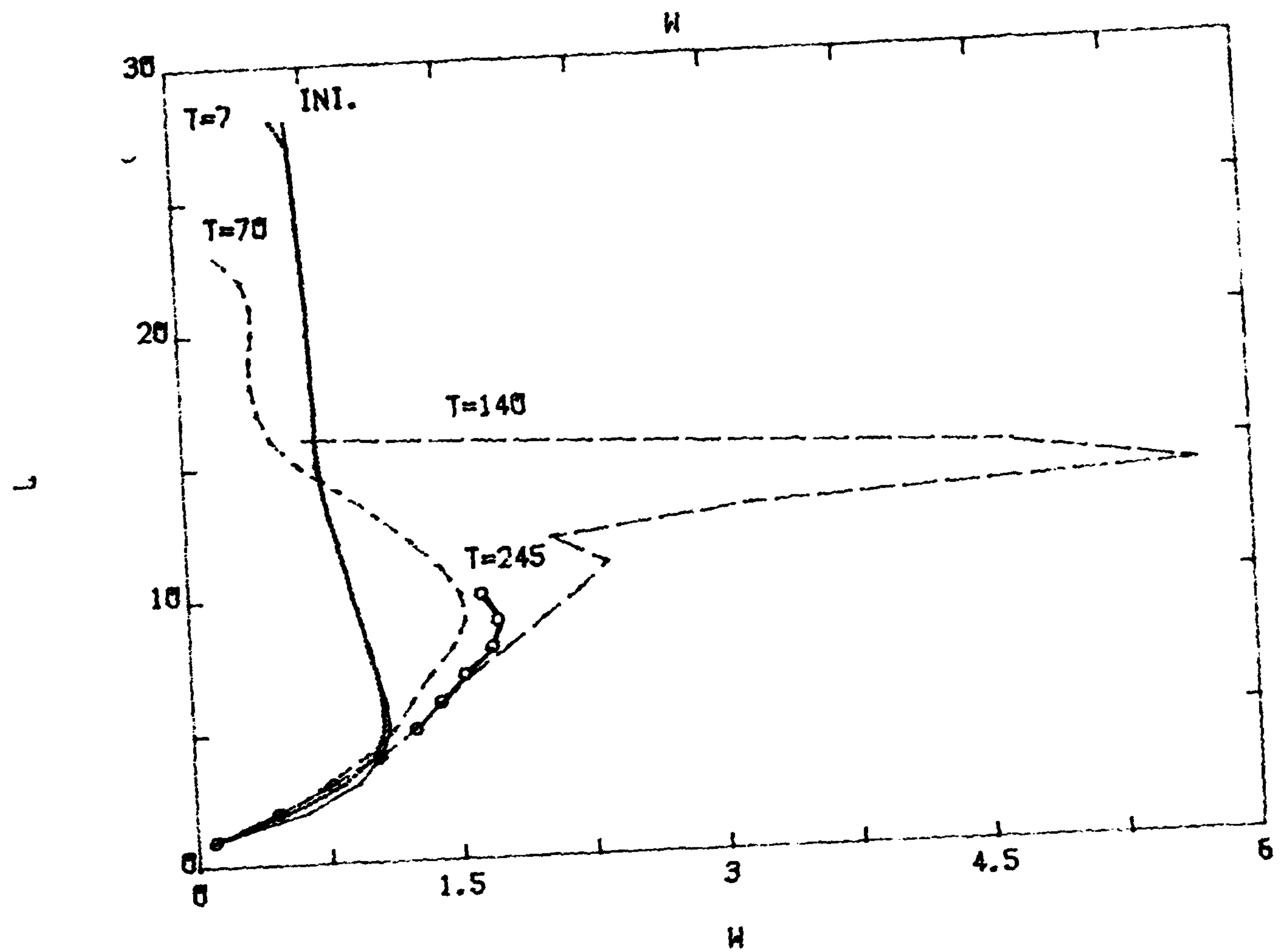

Fig. 18. Vertical Velocity $\times 10^{-2}$ (cm sec^{-1}) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds) Case 4.

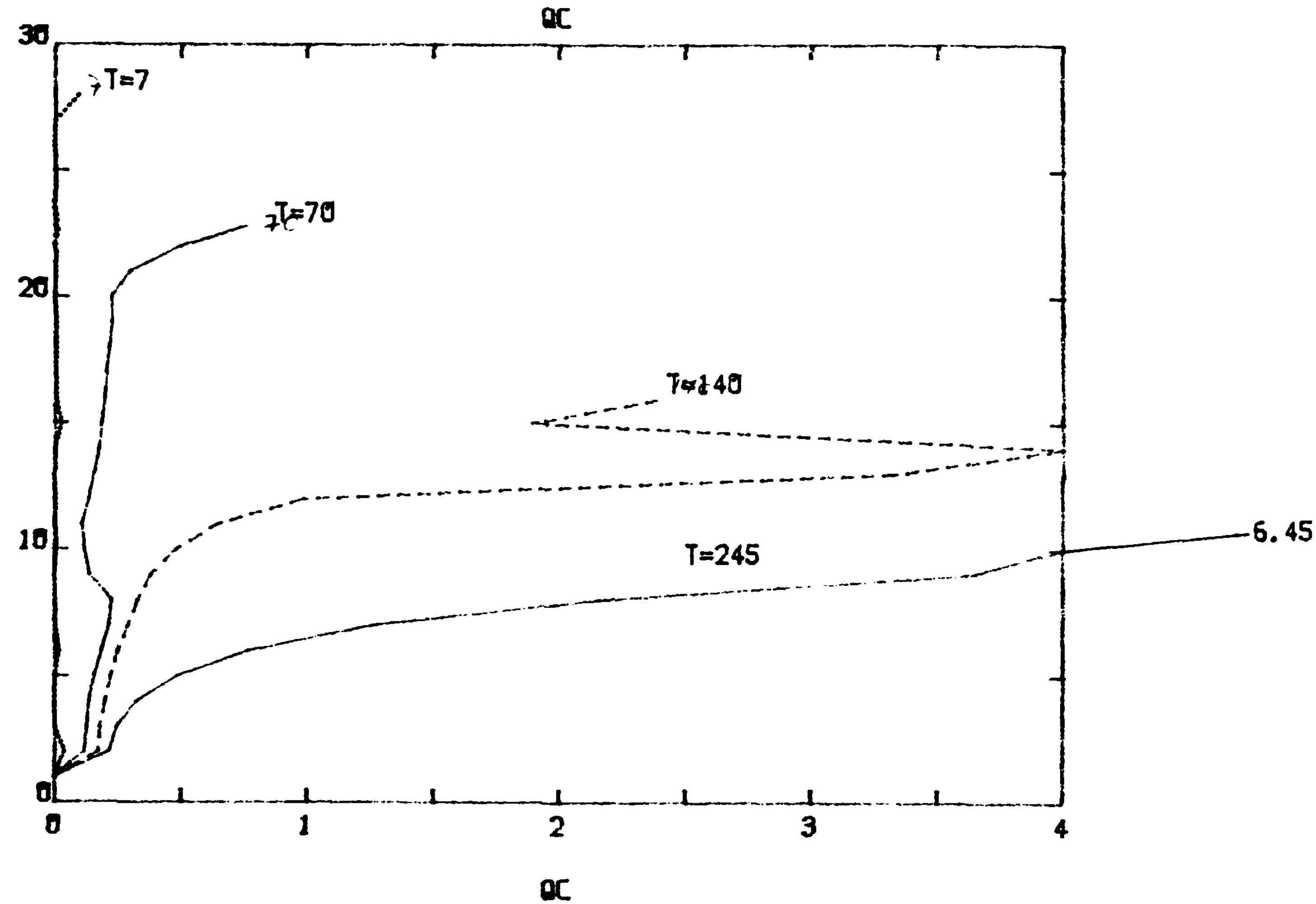

Fig. 19. Cloud Water Content x10^2 (gmgm^{-1}) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 4.

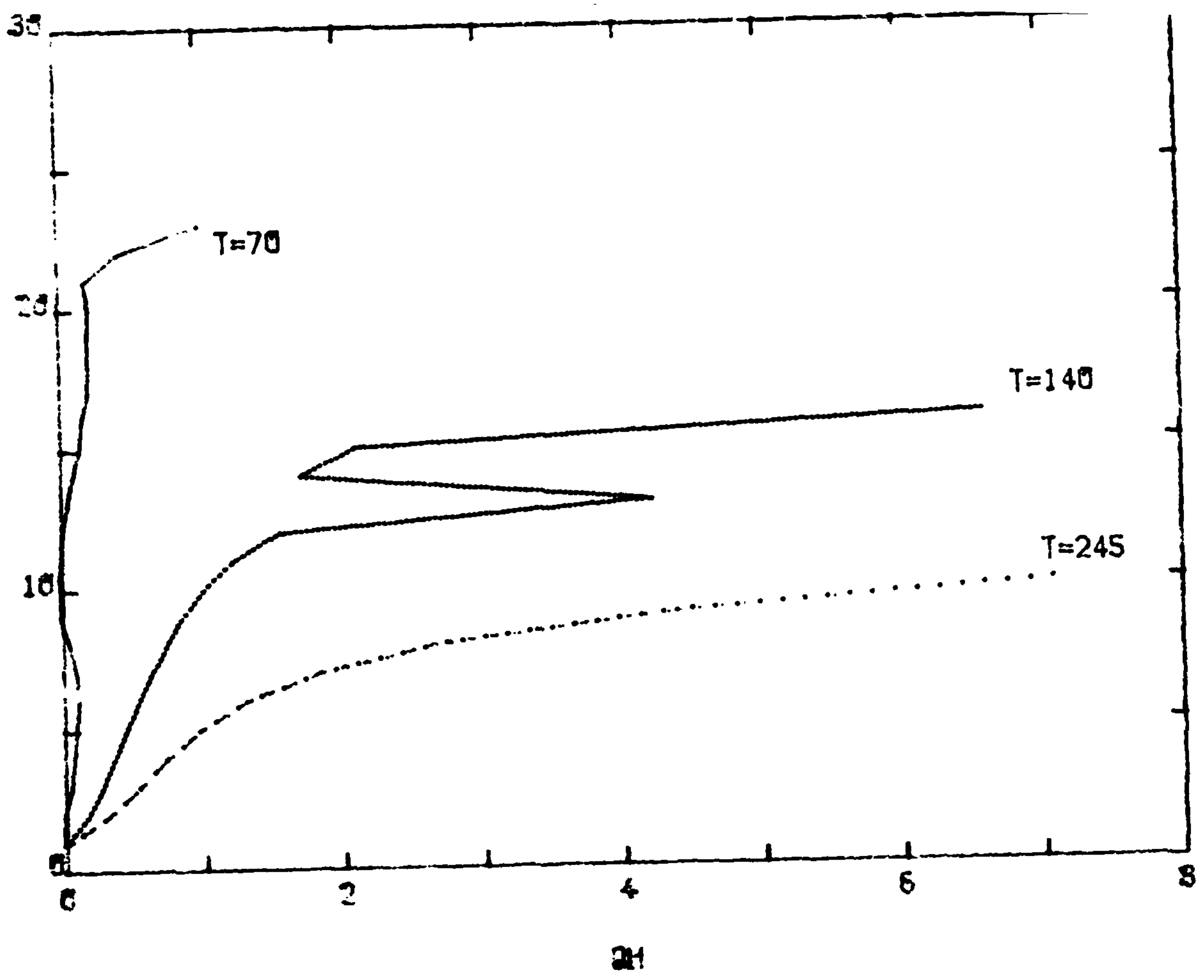

Fig. 20. Hydrometeor Water Content x10^2 ($gmgm^{-1}$) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 4.

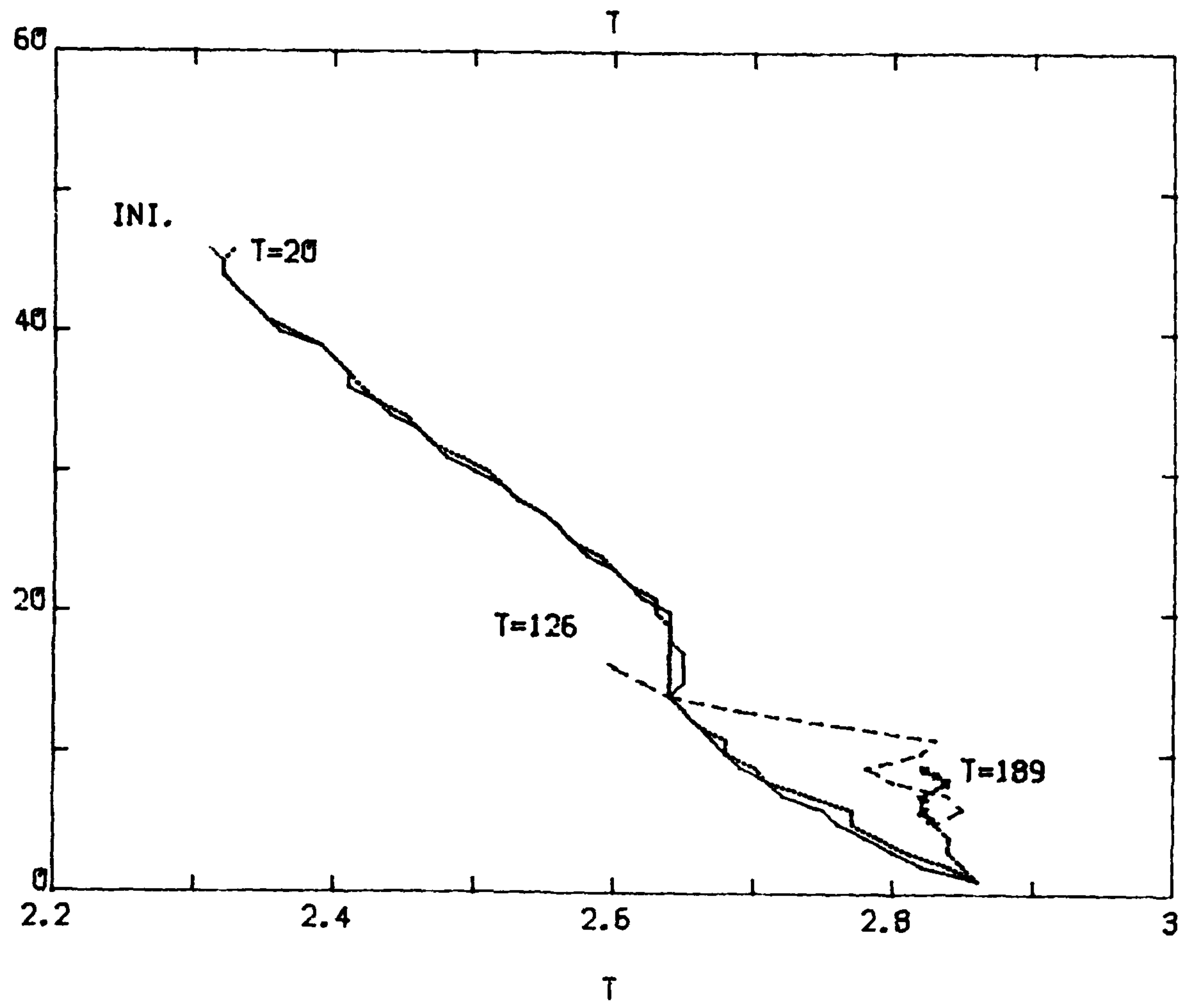

Fig. 21. Cloud Temperature x10^{-2} (Degrees K) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 5.

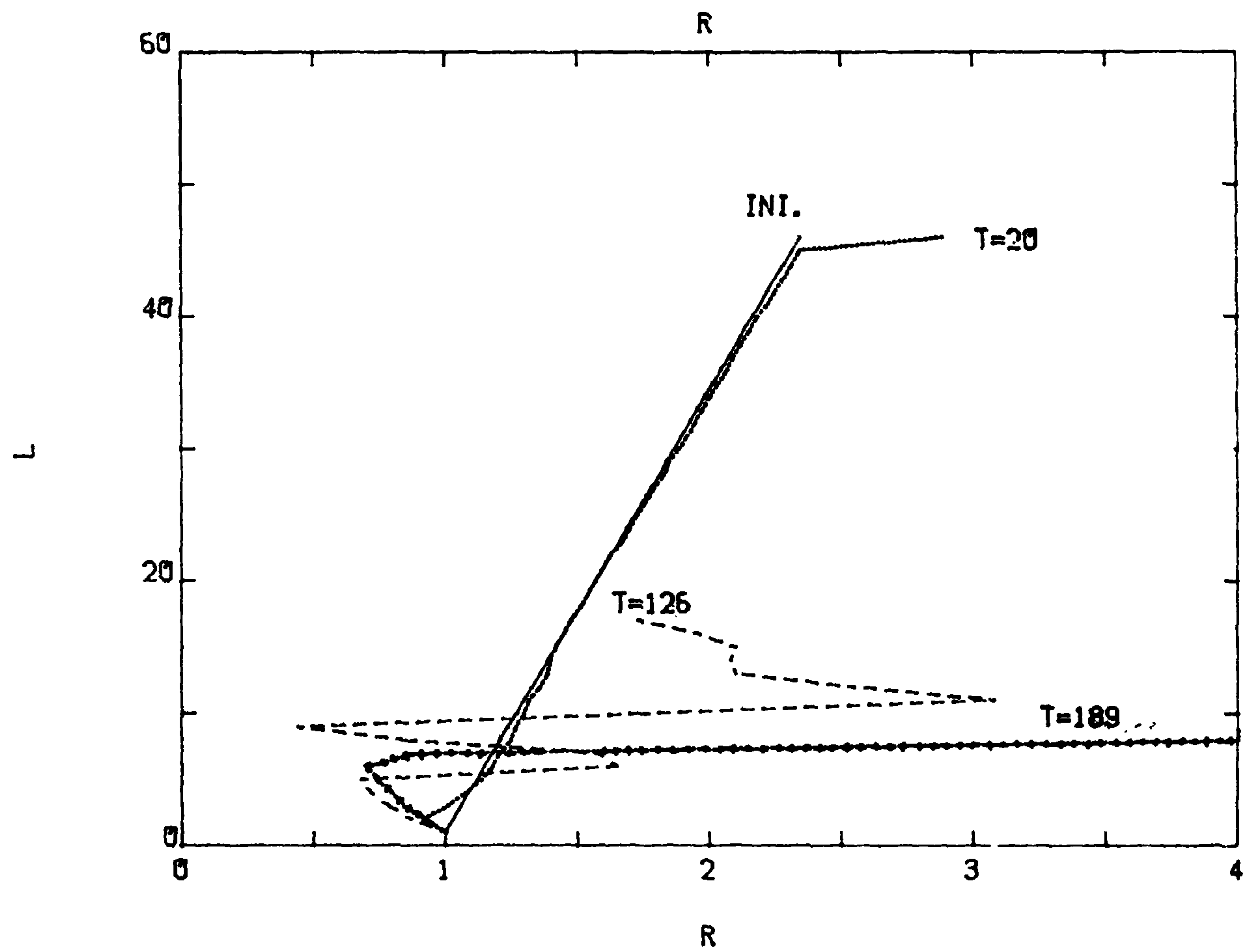

Fig. 22. Cloud Radius x10^{-5} (cm) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 5.

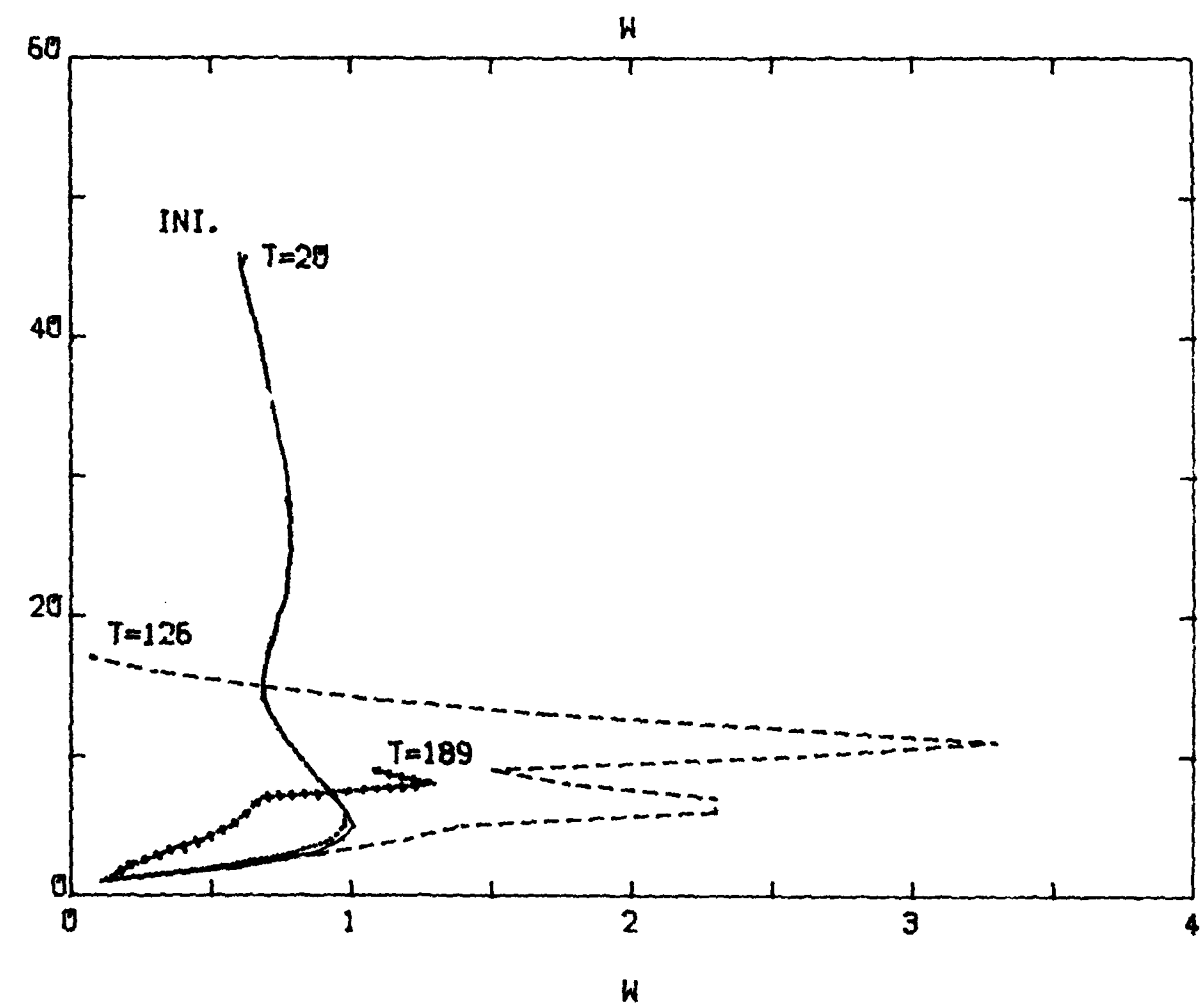

Fig. 23. Vertical Velocity x10^{-2} (cm sec^{-1}) vs Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 5.

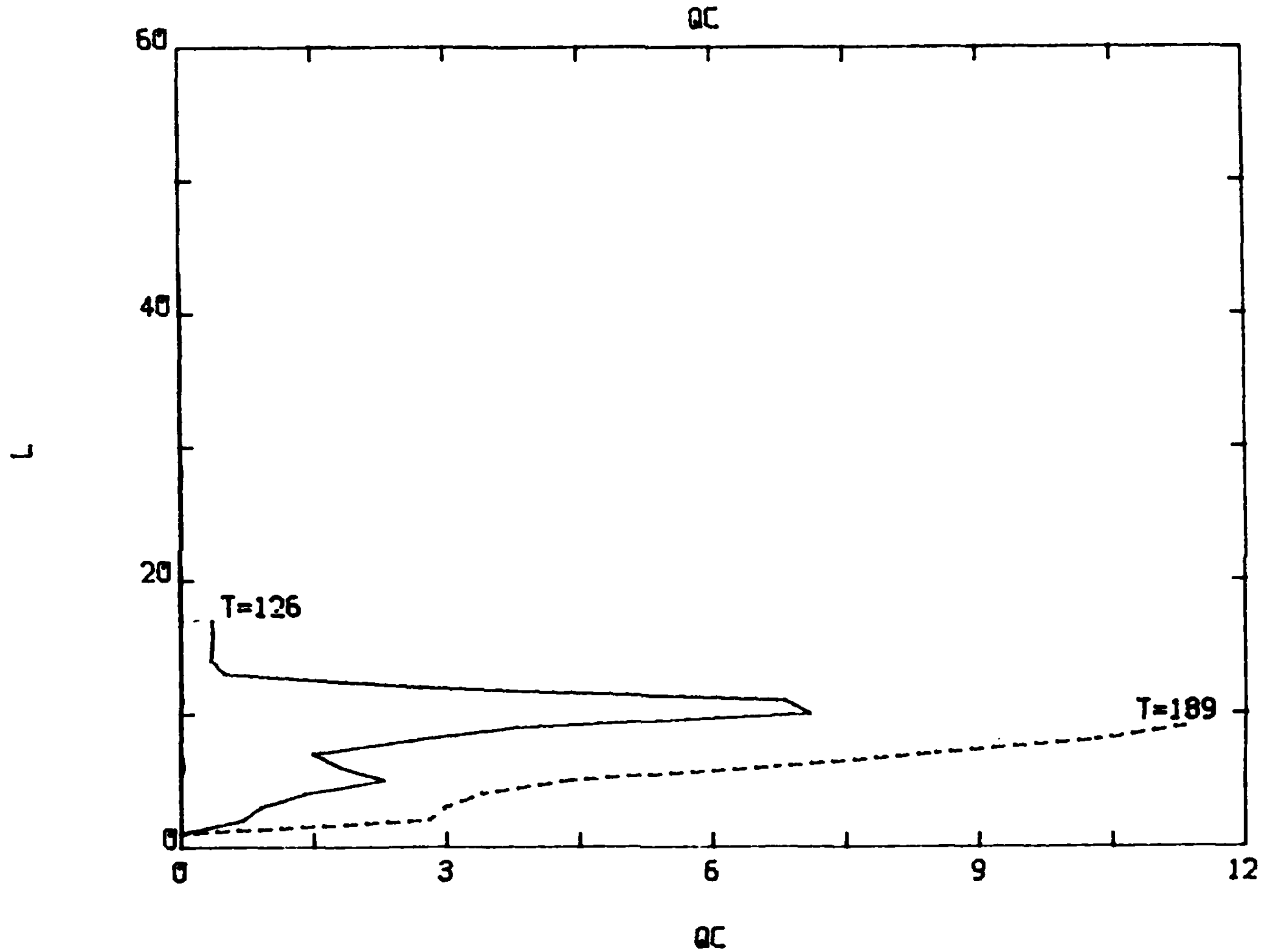

Fig. 24. Cloud Water Content x10^2 ($gmgm^{-1}$) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 5.

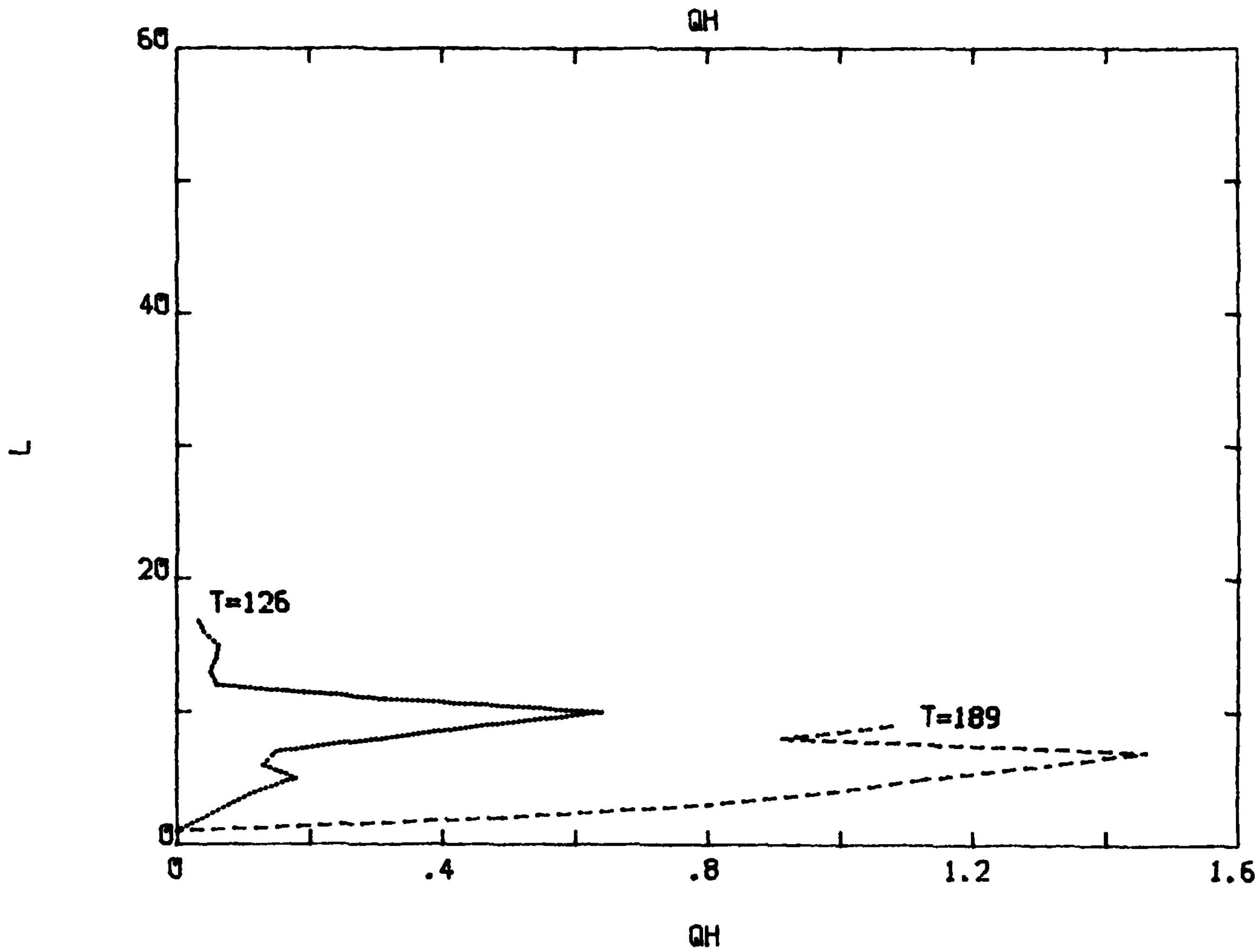

Fig. 25. Hydrometeor Water Content x10^2 ($gmgm^{-1}$) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 5.

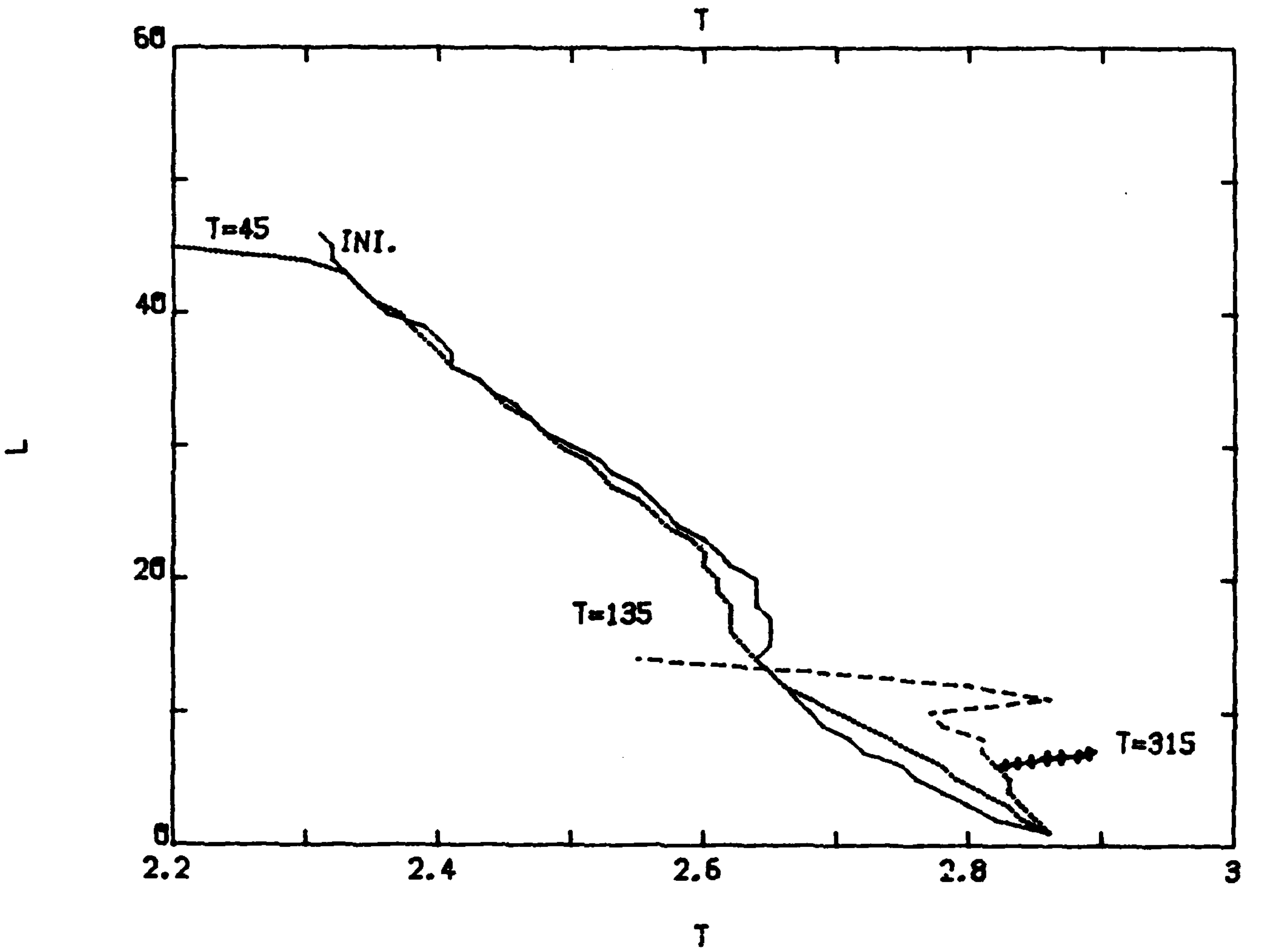

Fig. 26. Cloud Temperature x10^{-2} (Degrees k) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 6.

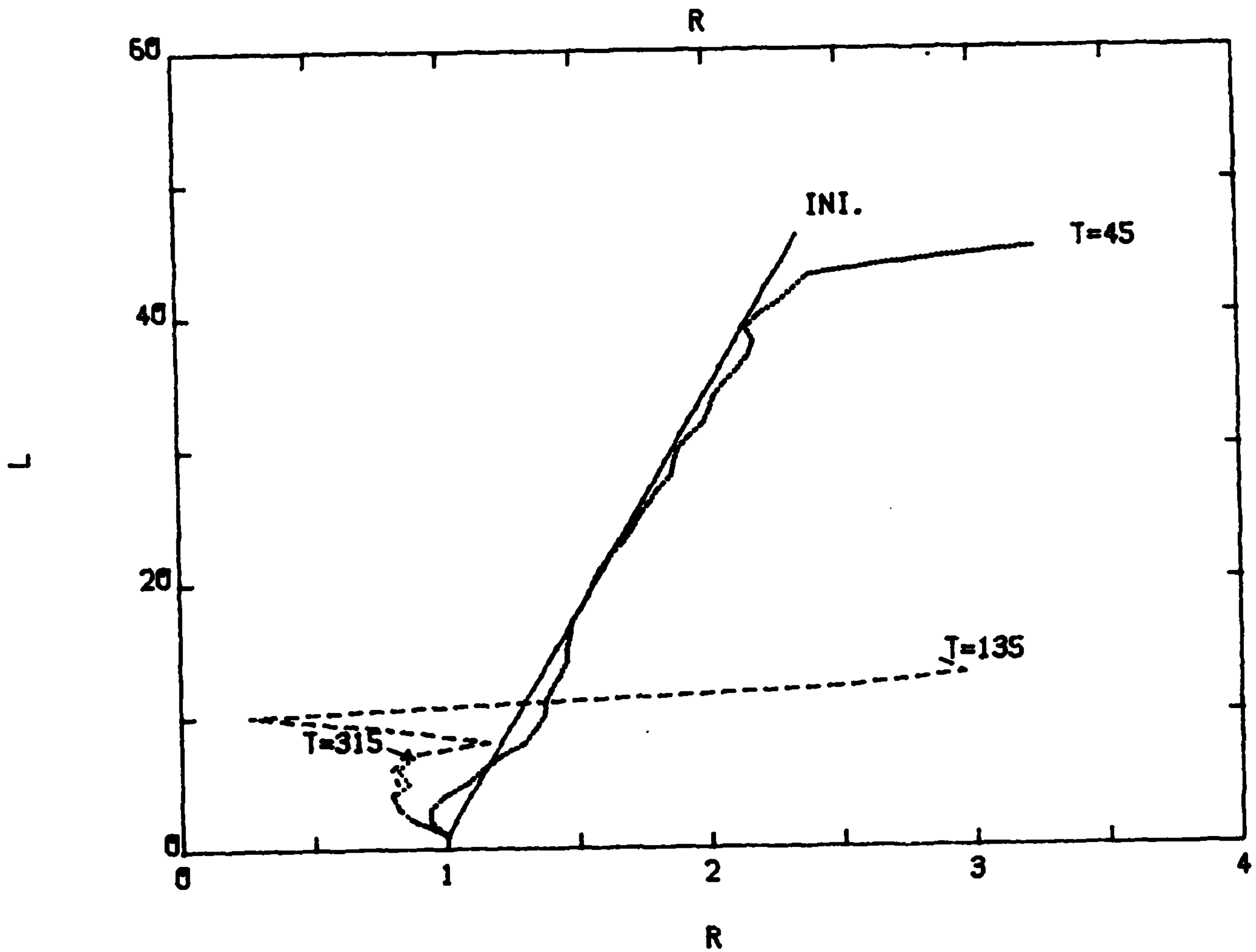

Fig. 27. Cloud Radius x10-5 (cm) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 6.

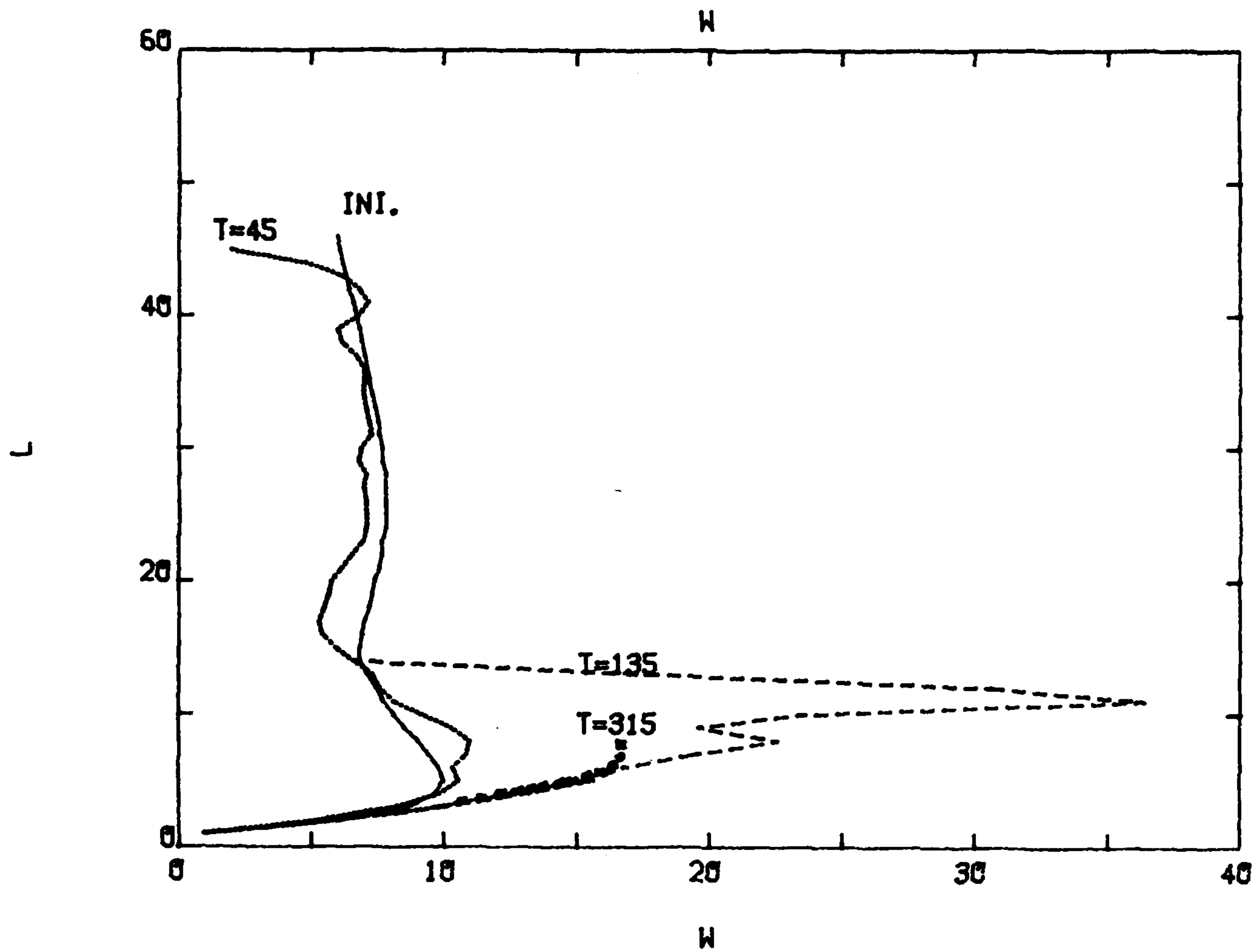

Fig. 28. Vertical Velocity x10^{-2} (cm sec^{-1}) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 6.

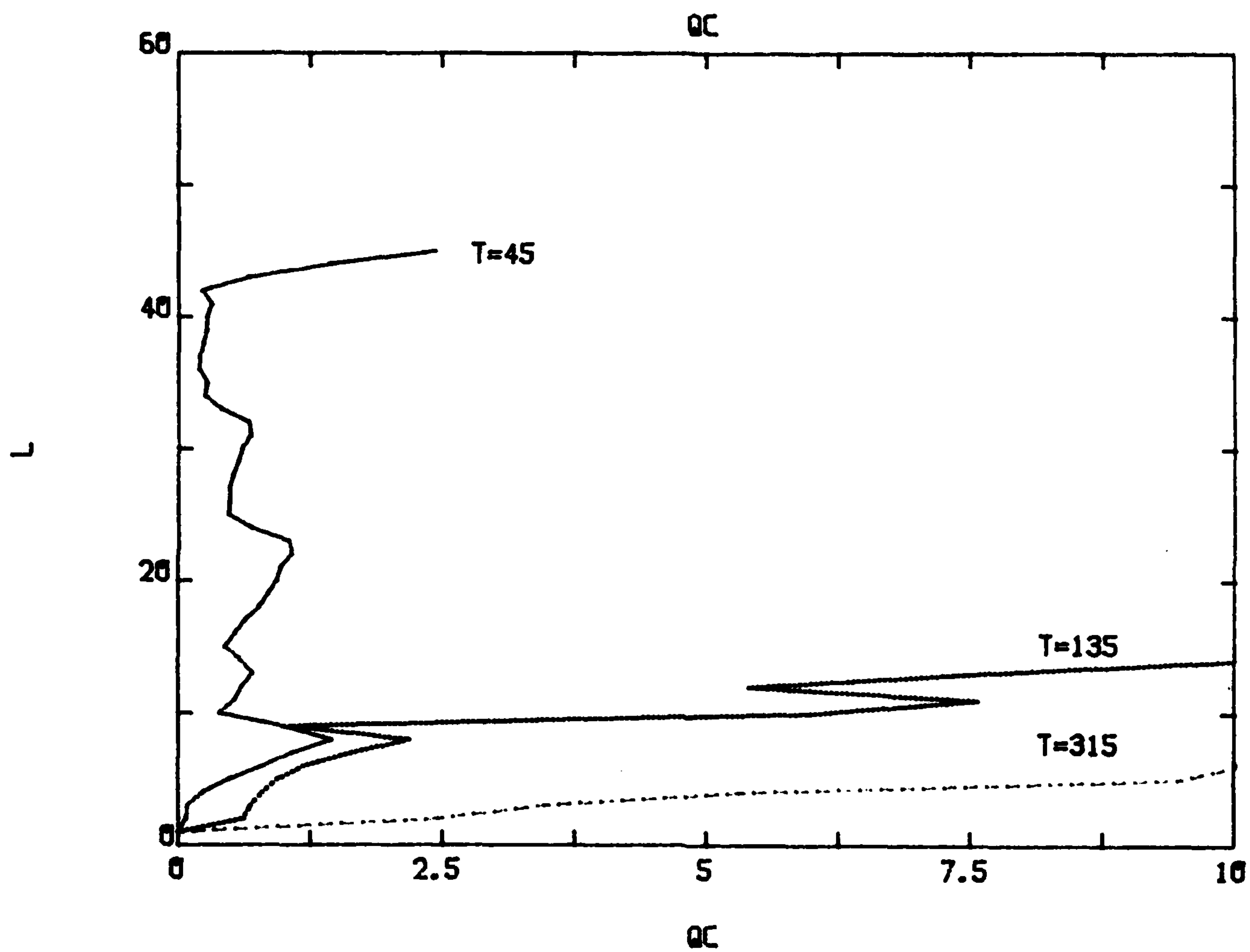

Fig. 29. Cloud Water Content x10^2 (gmgm^{-1}) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 6.

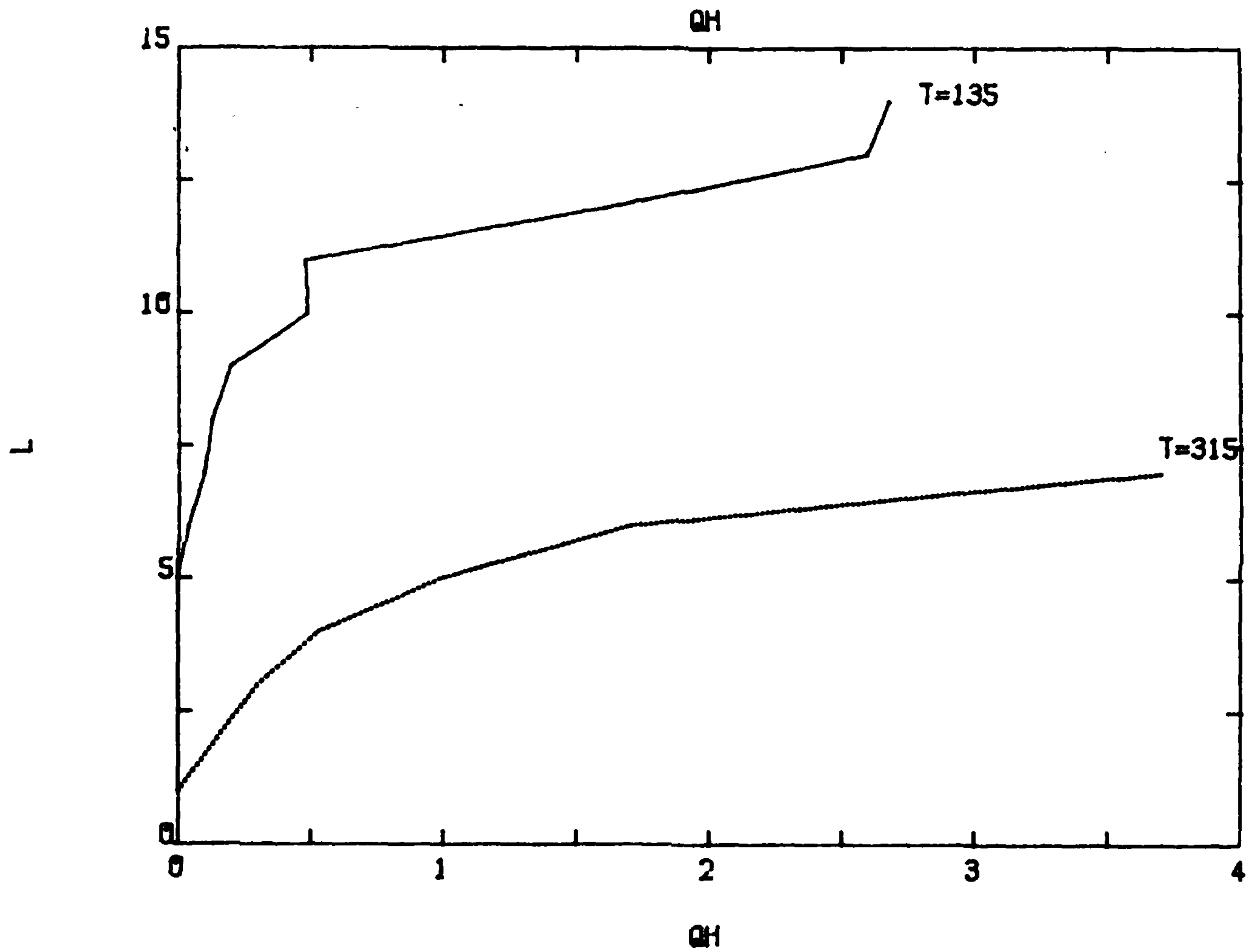

Fig. 30. Hydrometeor Water Content x10^2 ($gmgm^{-1}$) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 6.

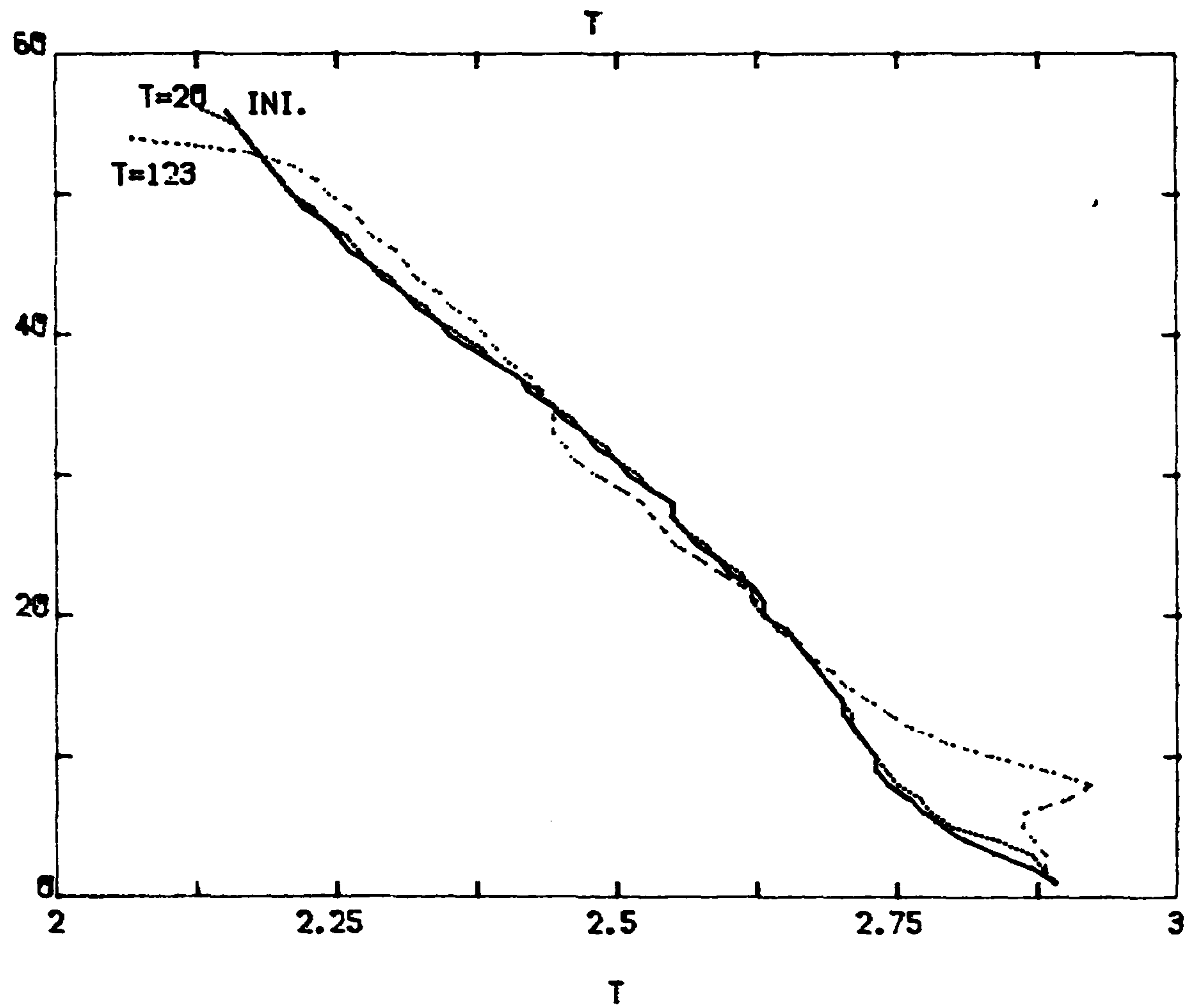

Fig. 31. Cloud Temperature x10^{-2} (Degrees K) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 7.

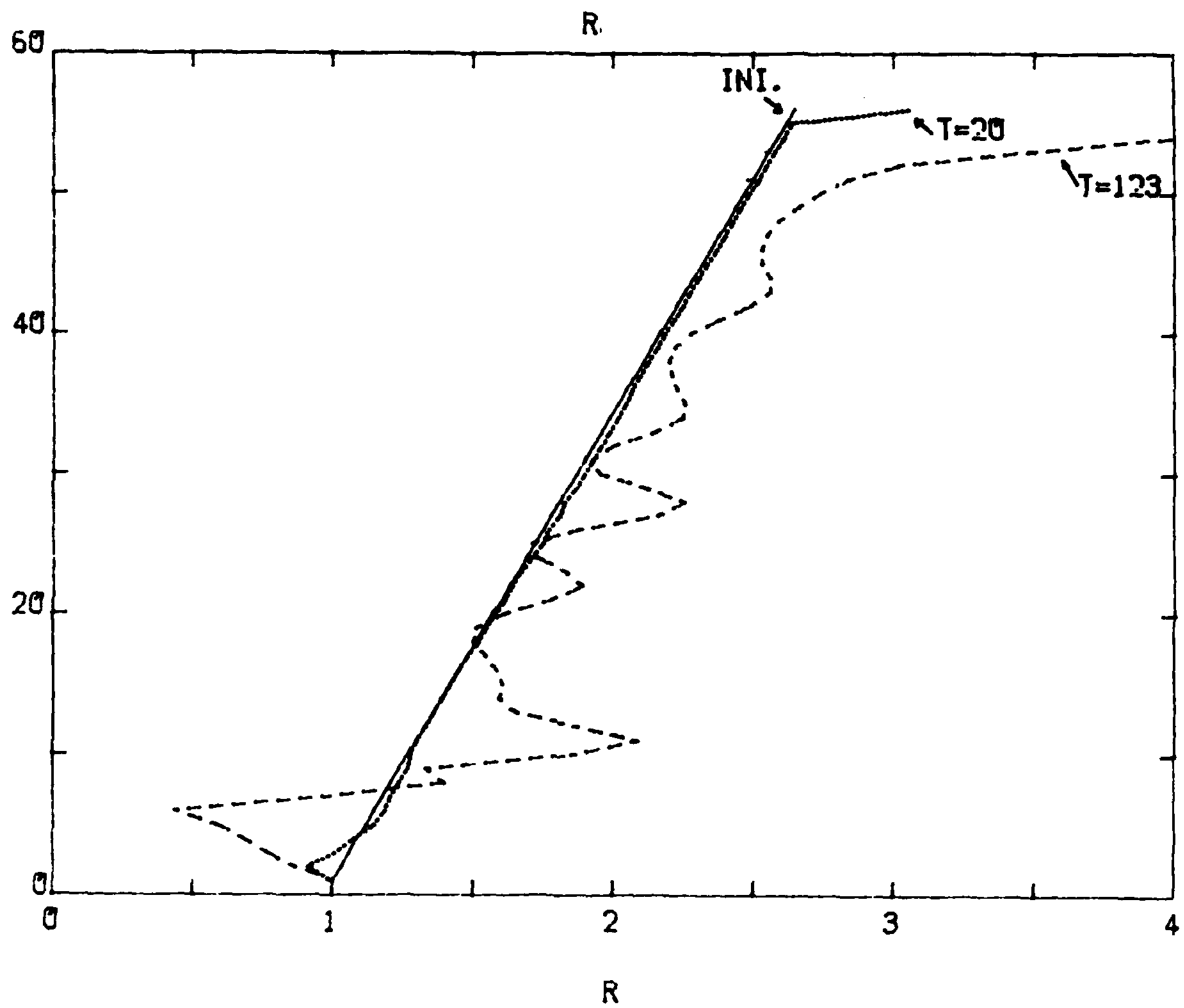

Fig. 32. Cloud Radius x10^{-5} (cm) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 7.

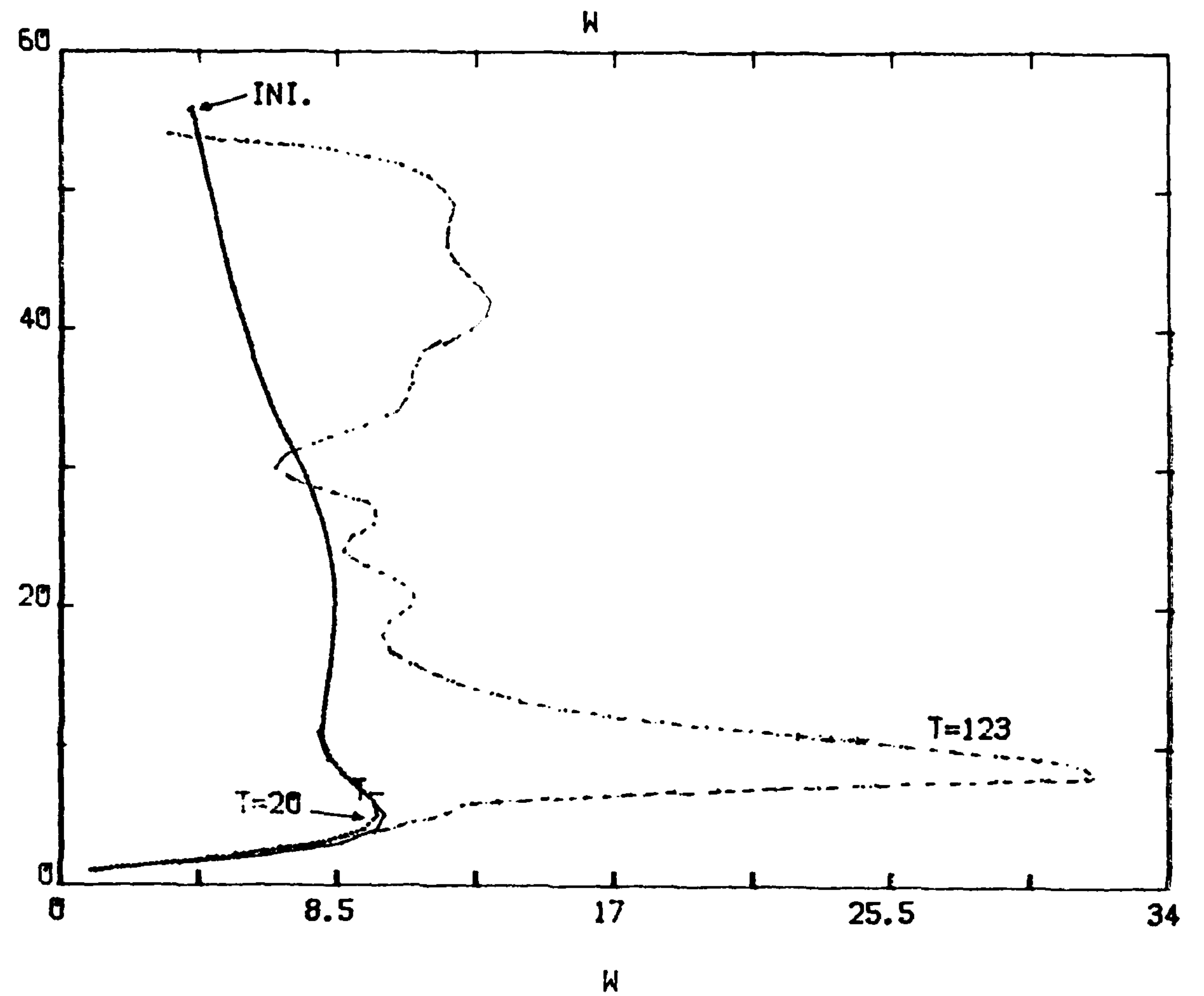

Fig. 33. Vertical Velocity x10^{-2} (cm sec^{-1}) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 7.

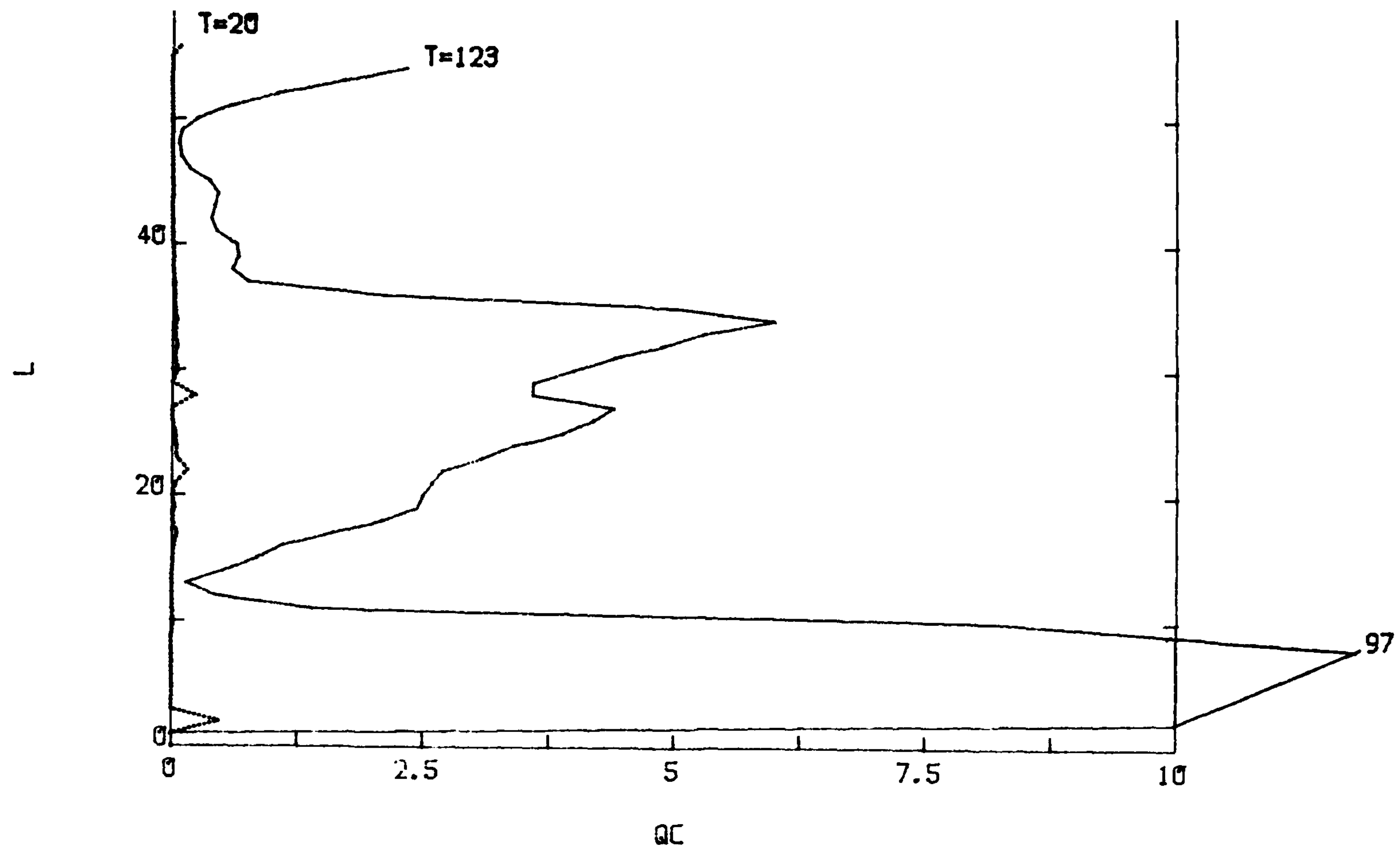

Fig. 34. Cloud Water Content x10^2 ($gmgm^{-1}$) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 7.

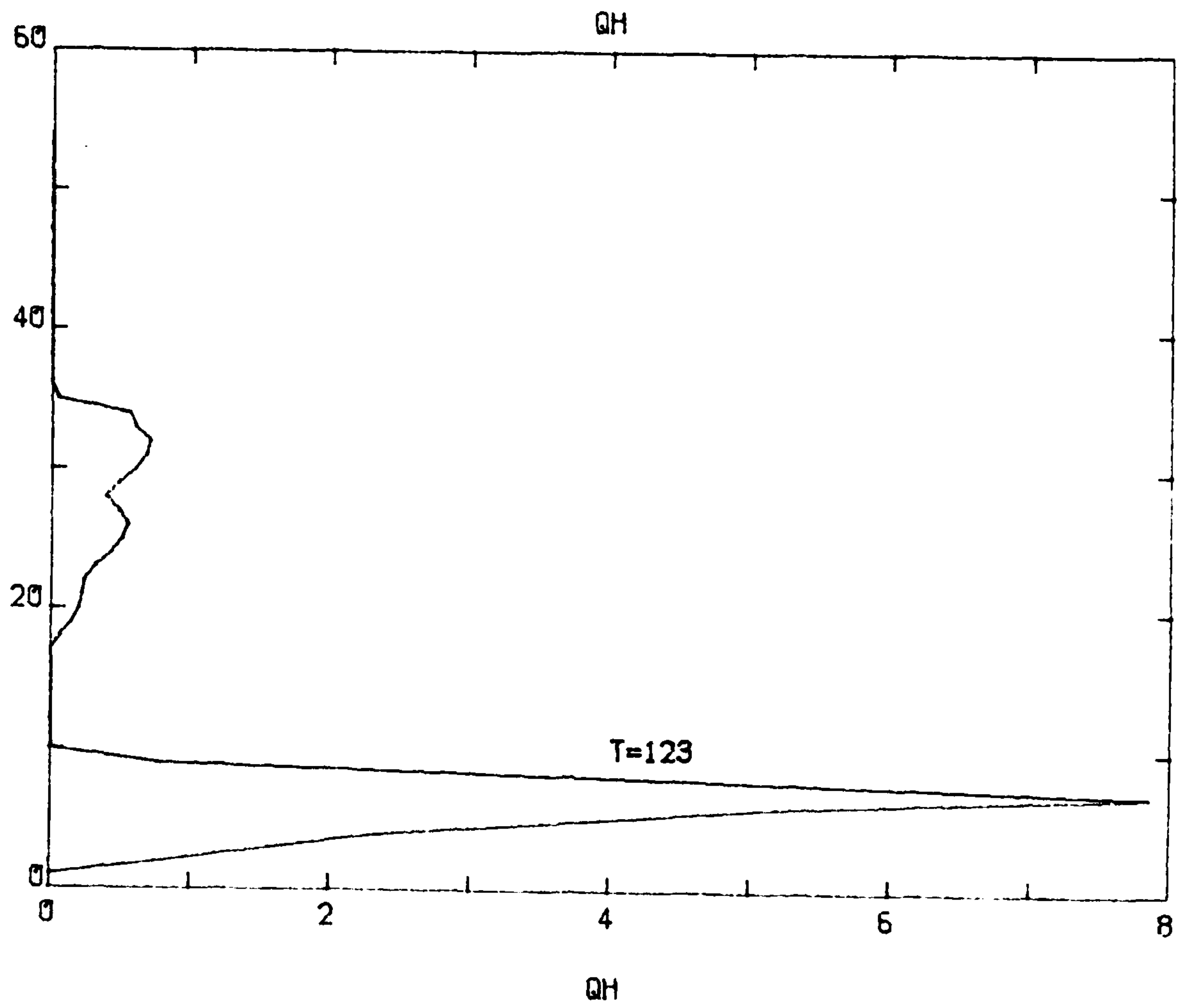

Fig. 35. Hydrometeor Water Content x10^2 ($gmgm^{-1}$) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 7.

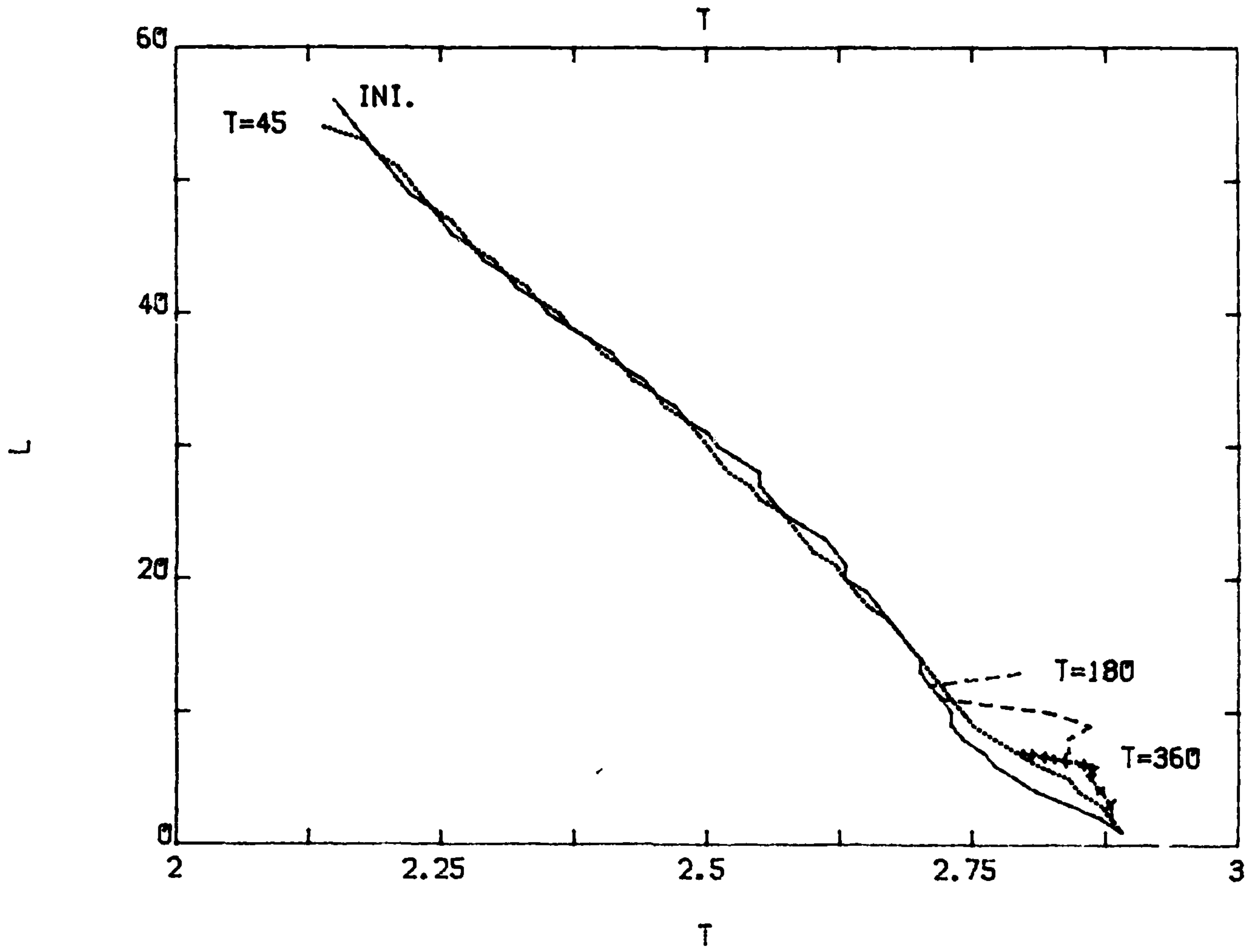

Fig. 36. Cloud Temperature x10^{-2} (Degrees K) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 8.

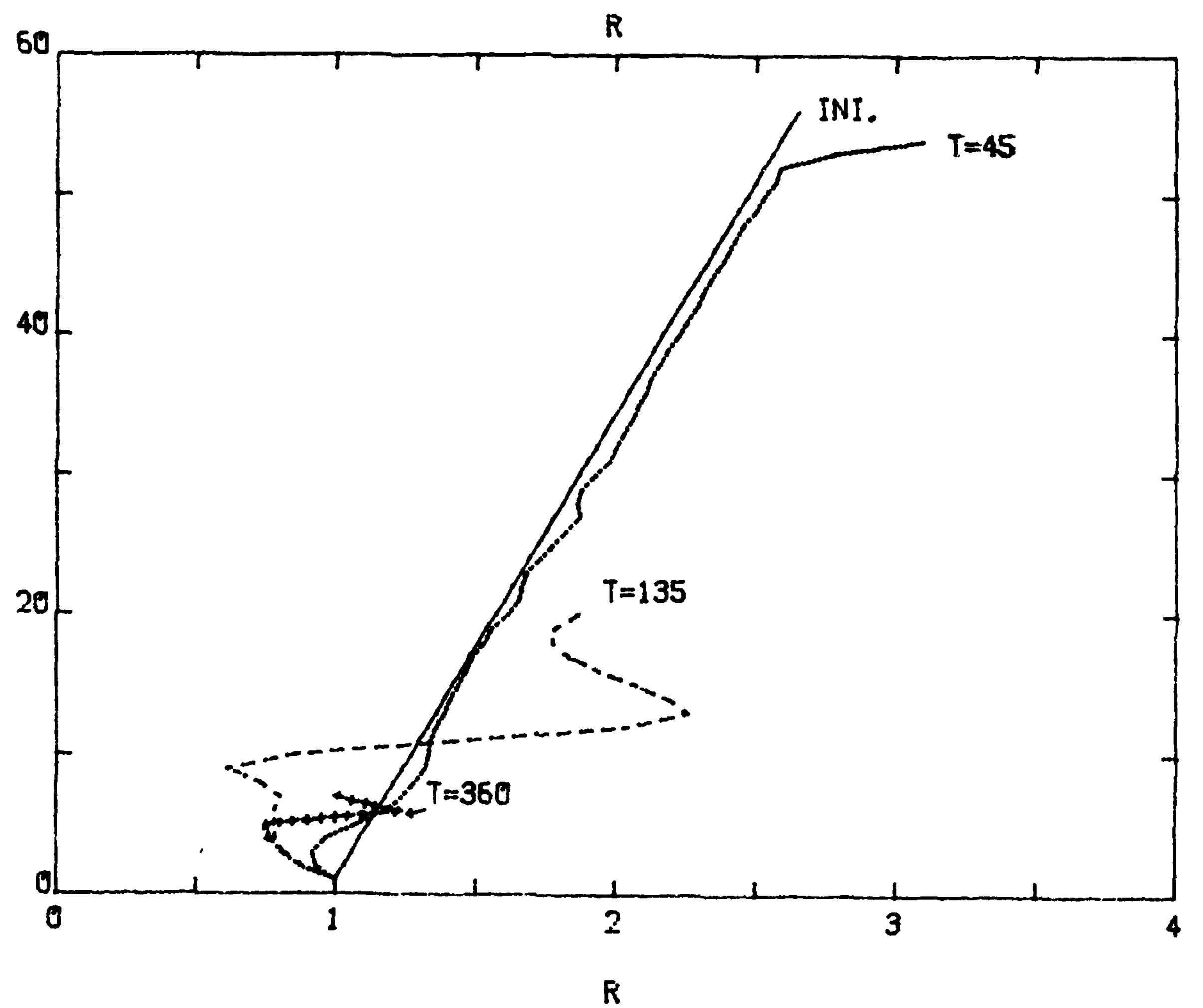

Fig. 37. Cloud Radius x10^{-5} (cm) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 8.

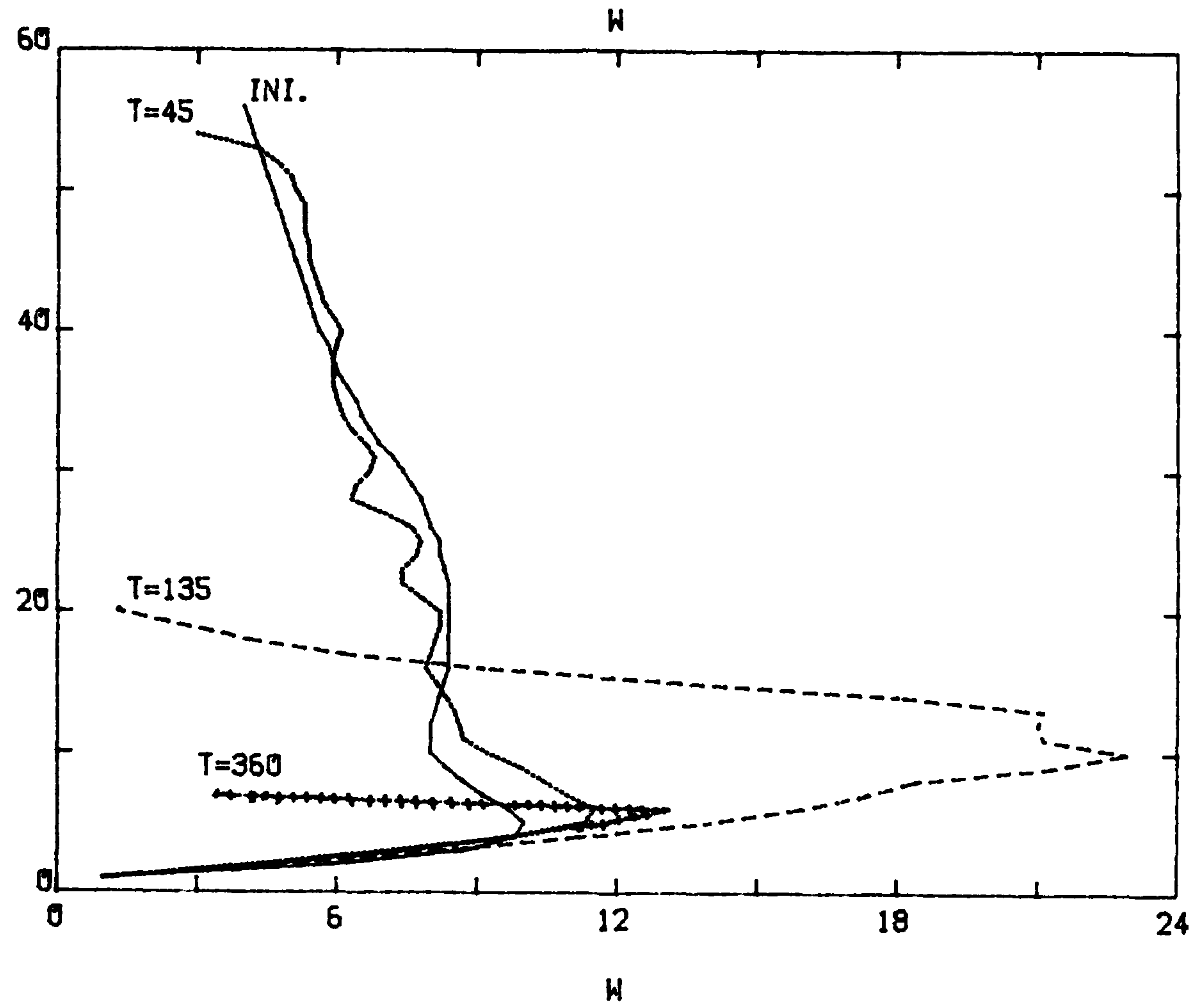

Fig. 38. Vertical Velocity $\times 10^{-2}$ (cm sec^{-1}) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 8.

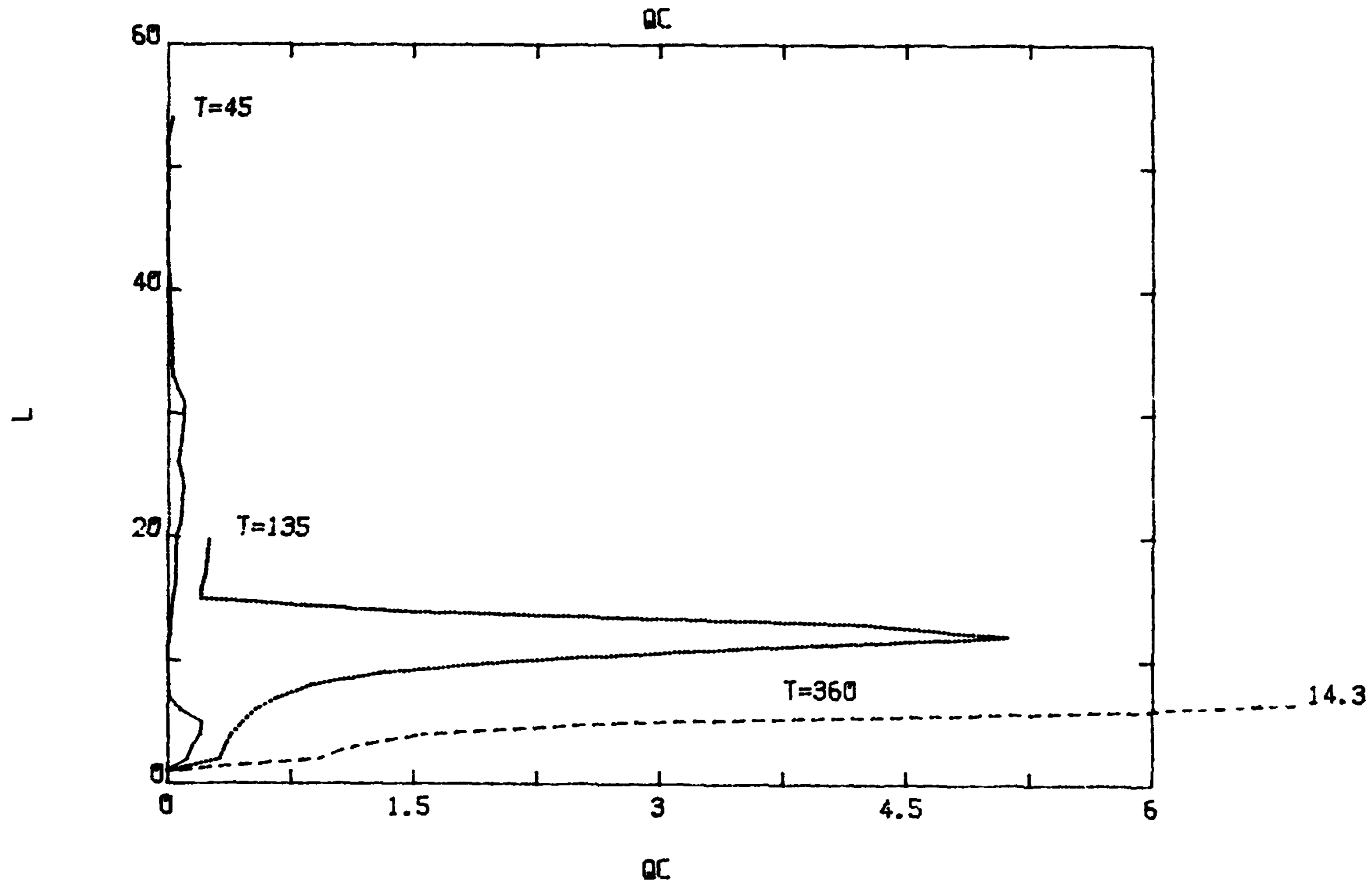

Fig. 39. Cloud Water Content $\times 10^2$ ($gmgm^{-1}$) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 8.

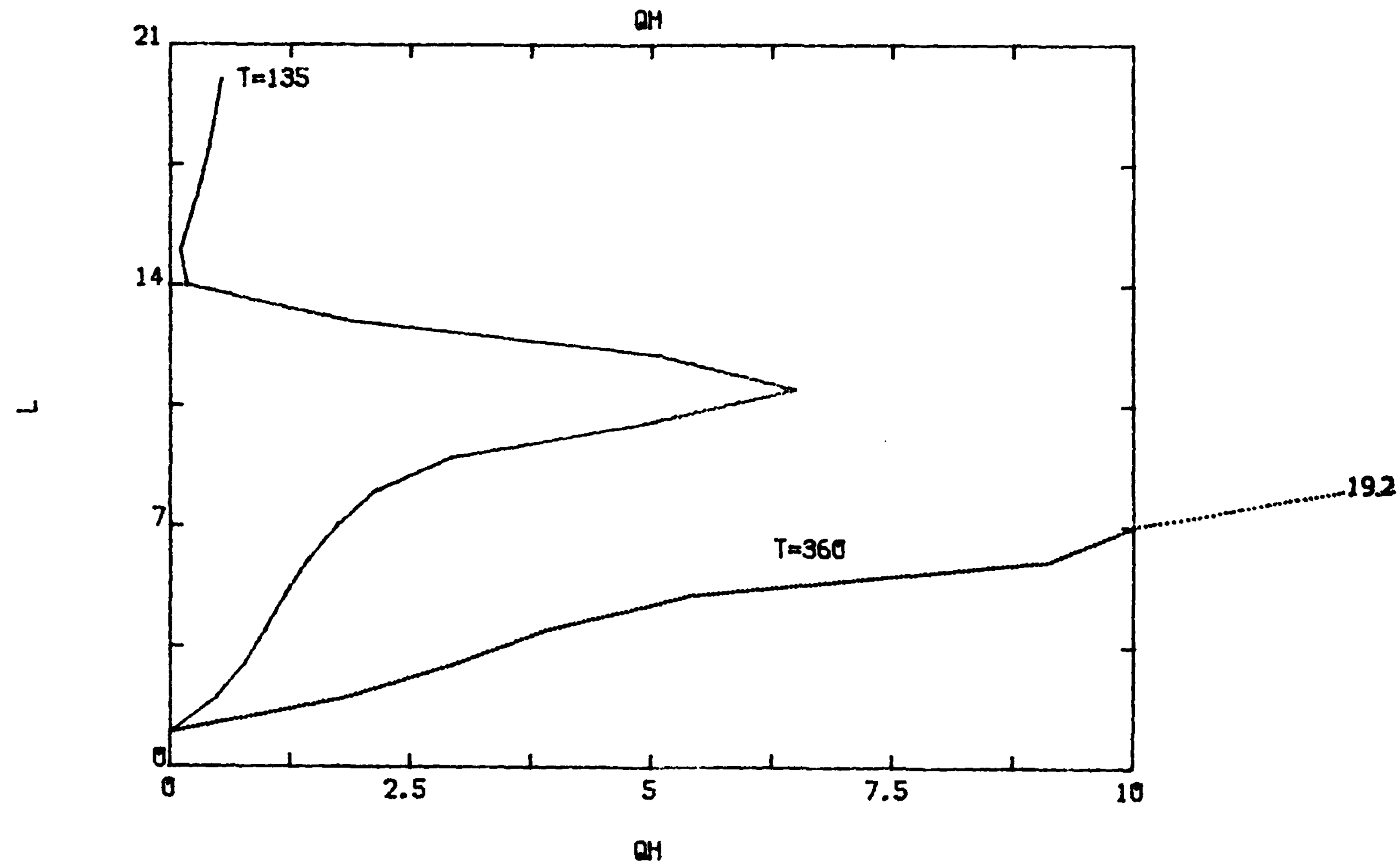

Fig. 40. Hydrometeor Water Content x10^{2} (gmgm^{-1}) vs. Level Number (Vertical Resolution is 200 m) as a Function of Time (seconds), Case 8.

Appendix - Computer Program

The attached program is in two parts. PROGRAM CLOUD 1 goes through the initialization procedure to calculate the initial values, and copies the results to files. PROGRAM CLOUD 2 carries out the calculations, according to the steps outlined in Procedure for Solving the System.

The calculations were done on the PDP 1134 computer at Kibbutz Sede Boqer. The program was written in BASIC PLUS language.

```
1       EXTEND
5       !--------------------------------------------------------! &
        !            P R O G R A M     C L O U D 1               ! &
        !--------------------------------------------------------!
15      DIM TE(61%),QE(61%),T(61%,2%),QC(61%,2%),QH(61%,2%) &
\       DIM QS(61%),W(61%,2%),R(61%,2%),RO(61%,2%),P(61%,2%) &
\       DIM MU(61%,2%),V(61%,2%),QSI(61%),DQS(61%)
50      !--------------------------------------------------------! &
        !  C O N S T A N T S    A N D    D E F I N I T I O N S   ! &
        !--------------------------------------------------------!
55      ALFA=0.15  \  A1=2.39*(10**(-8))  \  G=980  \  CP=0.239 &
\       J=4.185*(10**7)  \  RC=2.87*(10**6)  \  EPS=0.621 &
\       A=0.1*(10**(-5))
100     !--------------------------------------------------------! &
        !         INPUT  DATA  FROM  TERMINAL                    ! &
        !--------------------------------------------------------!
105     PRINT "C L O U D 1    ";TIME$(0%);"     ";DATE$(0%) \ PRINT &
\       INPUT "DZ VALUE";DZ \ PRINT &
\       INPUT "LEVELS NUMBER - MAXIMUM 60";LEV% \ PRINT &
\       INPUT "W(1,1) VALUE";W(1%,1%) \ PRINT &
\       INPUT "P(1,1) VALUE";P(1%,1%) \ PRINT &
\       INPUT "FILE NUMBER";D$ \ PRINT
200     !--------------------------------------------------------! &
        !        P R I N T      D A T A                          ! &
        !--------------------------------------------------------!
205     PRINT \ PRINT "            C O N S T A N T S" &
\             PRINT "     ===========================" \ PRINT &
\       PRINT " ALFA=";ALFA;"  A1=";A1;"  G=";G;"  CP=";CP;"  J=";J; &
        "  RC=";RC;"  EPS=";EPS;"  A=";A \ PRINT &
\       PRINT "          D A T A    F R O M    T E R M I N A L" &
\       PRINT "     ============================================" \ PRINT &
\       PRINT "  W(1,1)=";W(1%,1%);"  P(1,1)=";P(1%,1%);"  DZ=";DZ; &
        "  LEVELS=";LEV%;"  FILE NUMBER=";D$ \ PRINT \ PRINT
250     !--------------------------------------------------------! &
        !    OPEN  FILES  AND  COPY  DATA  TO  ARRAYS            ! &
        !--------------------------------------------------------!
255     OPEN "CLTE."+D$ FOR INPUT AS FILE 1%,MODE 8192% &
\       INPUT #1%,TE(I%) FOR I%=1% TO LEV% \ CLOSE 1% &
\       OPEN "CLQE."+D$ FOR INPUT AS FILE 1%,MODE 8192% &
\       INPUT #1%,QE(I%) FOR I%=1% TO LEV% \ CLOSE 1% &
\       OPEN "CLT."+D$ FOR INPUT AS FILE 1%,MODE 8192% &
\       INPUT #1%,T(I%,1%) FOR I%=1% TO LEV% \ CLOSE 1%
300     !--------------------------------------------------------! &
        !    P R I N T   D A T A   F R O M   F I L E S           ! &
        !--------------------------------------------------------!
305     ST1$=" LEVEL " \ ST1$=ST1$+"     TE(I)          QE(I)     " &
\       ST1$=ST1$+"     T(I,N)" \ ST2$=" -----  " &
\       ST2$=ST2$+"------------    " FOR I%=1% TO 3% &
\       ST3$="   ##" \ ST3$=ST3$+"    #.######^^^^" FOR I%=1% TO 3% \ PRINT &
\       PRINT "          D A T A    F R O M    F I L E S" &
\       PRINT "     =======================================" \ PRINT &
\       PRINT ST1$ \ PRINT ST2$ &
\       PRINT USING ST3$,I%,TE(I%),QE(I%),T(I%,1%) FOR I%=1% TO LEV%
500     !--------------------------------------------------------! &
        !     CALCULATE   INITIAL   VALUES                       ! &
        !--------------------------------------------------------!
505     T(1%,2%)=T(1%,1%) \ QC(1%,1%),QC(1%,2%)=0 &
\       QH(1%,1%),QH(1%,2%)=0 &
```

```
\       R(1%,1%),R(1%,2%)=10**5 \ P(1%,2%)=P(1%,1%)
550     !-----------------------------------------------------------! &
        !  STEP 1 - CALCULATE P(I,N) FOR N=1, FOR I=2 TO LEV        ! &
        !-----------------------------------------------------------!
555     FOR I%=2% TO LEV% &
\           EZ1=0 &
\           EZ1=EZ1+DZ/T(K%,1%) FOR K%=1% TO I% &
\           P(I%,1%)=P(1%,1%)*EXP((-G/RC)*EZ1) &
\       NEXT I%
600     !-----------------------------------------------------------! &
        !  STEP 2 - CALCULATE RO FOR N=1, FOR I=1 TO LEV            ! &
        !-----------------------------------------------------------!
605     RO(I%,1%)=P(I%,1%)/(RC*T(I%,1%)) FOR I%=1% TO LEV% &
\       RO(LEV%+1%,1%)=2*RO(LEV%,1%)-RO(LEV%-1%,1%) &
\       RO(1%,2%)=P(1%,2%)/(RC*T(1%,2%))
650     !-----------------------------------------------------------! &
        !  STEP 2A - CALCULATE QC,QH,V FOR N=1, FOR I=1 TO LEV+1    ! &
        !-----------------------------------------------------------!
655     QC(I%,1%)=0 FOR I%=1% TO LEV%+1% &
\       QH(I%,1%)=0 FOR I%=1% TO LEV%+1% &
\       V(I%,1%)=0 FOR I%=1% TO LEV%+1%
700     !-----------------------------------------------------------! &
        !  STEP 3  - CALCULATE MU - EQUATION 47                     ! &
        !  STEP 5  - CALCULATE W  - EQUATION 43                     ! &
        !  STEP 5A - CALCULATE R  - EQUATION 44                     ! &
        !  STEP 4  - CALCULATE QS - EQUATION 40                     ! &
        !  STOP  CALCULATION  WHERE W=<0                            ! &
        !-----------------------------------------------------------!
710     FOR I%=1% TO LEV% &
\           M%=I%+1% &
\           MU(I%,1%)=2*ALFA/R(I%,1%) \ E2=LOG10(T(I%,1%)) &
\           E1=-2937.4/T(I%,1%)-4.9283*E2+22.5518 &
\           E3=P(I%,1%)*0.0001 &
\           QS(I%)=(EPS/E3)*(10**E1) &
\           E1=(1+0.61*QS(I%))*T(I%,1%) \ E2=(1+0.61*QE(I%))*TE(I%) &
\           E3=2*MU(I%,1%)*(W(I%,1%)**2)*DZ \ E4=(E1-E2)/E2 &
\           E5=(W(I%,1%)**2)+2*G*DZ*E4-E3 &
\           IF E5>=0 AND W(I%,1%)>0 &
            THEN 790 &
            ELSE LEV%=I% \ GO TO 1000
790         W(M%,1%)=SQR(E5) \ E1=LOG(W(M%,1%))-LOG(W(I%,1%)) &
\           E2=LOG(RO(M%,1%))-LOG(RO(I%,1%)) \ E3=R(I%,1%)/2 &
\           R(M%,1%)=R(I%,1%)+ALFA*DZ-E3(E1+E2)
820     NEXT I%
1000    !-----------------------------------------------------------! &
        !                 P R I N T    R E S U L T S                ! &
        !-----------------------------------------------------------!
1005    ST1$=" LEVEL       TE(I)      " &
\       ST1$=ST1$+"     QE(I)           T(I,N)     " &
\       ST1$=ST1$+"    QC(I,N)         QH(I,N)     " &
\       ST1$=ST1$+"    QS(I,N)          W(I,N)     " \ ST2$=" -----   " &
\       ST2$=ST2$+"------------      " FOR I%=1% TO 7% \ ST3$="    ##" &
\       ST3$=ST3$+"    #.######^^^^" FOR I%=1% TO 7% &
\       ST4$=" LEVEL       R(I,N)     " &
\       ST4$=ST4$+"    RO(I,N)         P(I,N)      " &
\       ST4$=ST4$+"    MU(I,N)          V(I,N)     " &
\       ST4$=ST4$+"    QSI(I,N)        DQS(I,N)    " \ PRINT &
\       PRINT "          RESULTS - INITIAL  VALUES" &
```

```
\       PRINT "     =================================" &
\       PRINT \ PRINT ST1$ \ PRINT ST2$ &
\       PRINT USING ST3$,I%,TE(I%),QE(I%),T(I%,1%),QC(I%,1%),QH(I%,1%), &
        QS(I%),W(I%,1%) FOR I%=1% TO LEV% &
\       PRINT \ PRINT \ PRINT \ PRINT ST4$ \ PRINT ST2$ &
\       PRINT USING ST3$,I%,R(I%,1%),RO(I%,1%),P(I%,1%),MU(I%,1%), &
        V(I%,1%),QSI(I%),DQS(I%) FOR I%=1% TO LEV% &
\       PRINT \ PRINT
1100    !-------------------------------------------------------------! &
        !             COPY  RESULTS  TO  FILES                        ! &
        !-------------------------------------------------------------!
1105    INPUT "SAVE RESULTS IN EXTERNAL FILES <YES OR NO>";DD$ &
\       GO TO 10000 IF DD$="NO" &
\       GO TO 1120 IF DD$="YES" &
\       PRINT "INCORECT ANSWER" \ GO TO 1105
1120    OPEN "CLP."+D$ FOR OUTPUT AS FILE 1% &
\       PRINT #1%,P(I%,1%) FOR I%=1% TO LEV% \ CLOSE 1% &
\       OPEN "CLQS."+D$ FOR OUTPUT AS FILE 1% &
\       PRINT #1%,QS(I%) FOR I%=1% TO LEV% \ CLOSE 1% &
\       OPEN "CLW."+D$ FOR OUTPUT AS FILE 1% &
\       PRINT #1%,W(I%,1%) FOR I%=1% TO LEV% \ CLOSE 1% &
\       OPEN "CLR."+D$ FOR OUTPUT AS FILE 1% &
\       PRINT #1%,R(I%,1%) FOR I%=1% TO LEV% \ CLOSE 1% &
\       OPEN "CLMU."+D$ FOR OUTPUT AS FILE 1% &
\       PRINT #1%,MU(I%,1%) FOR I%=1% TO LEV% \ CLOSE 1% &
\       OPEN "CLRO."+D$ FOR OUTPUT AS FILE 1% &
\       PRINT #1%,RO(I%,1%) FOR I%=1% TO LEV% \ CLOSE 1%
10000   END
```

```
1       EXTEND
5       !--------------------------------------------------------------! &
        !          P R O G R A M        C L O U D 2                    ! &
        !--------------------------------------------------------------!
10      !----------------------------------------------! &
        !      D E F I N I T I O N S                   ! &
        !----------------------------------------------!
15      DIM TE(61%),  QE(61%),  T(61%,2%),  QC(61%,2%), QH(61%,2%) &
\       DIM QS(61%),  W(61%,2%),  R(61%,2%),  RO(61%,2%),  P(61%,2%) &
\       DIM MU(61%,2%),  V(61%,2%),  QSI(61%),  DQS(61%)
50      !----------------------------------------------! &
        !      C O N S T A N T S                       ! &
        !----------------------------------------------!
55      ALFA=0.15  \  A1=2.39*(10**(-8))  \  G=980  \  CP=0.239 &
\       J=4.185*(10**7)  \  RC=2.87*(10**6)  \  EPS=0.621 &
\       A=0.000001  \  E78=7/8 &
\       ST1$="   LEVEL        T(I,N)          W(I,N)          R(I,N)     " &
\       ST1$=ST1$+"     P(I,N)          QC(I,N)          QH(I,N)     " &
\       ST2$="   LEVEL        RO(I,N)          MU(I,N)          V(I,N)     " &
\       ST2$=ST2$+"     QS(I)           QSI(I)           DQS(I)      " &
\       ST3$="   -----      ------------    ------------    ------------     " &
\       ST3$=ST3$+" ------------    ------------    ------------     " &
\       ST4$="     ##       #.######^^^^    #.######^^^^    #.######^^^^     " &
\       ST4$=ST4$+" #.######^^^^    #.######^^^^    #.######^^^^     " &
\       SUMTIM=0
100     !-----------------------------------------------------! &
        !   I N P U T   D A T A   F R O M   T E R M I N A L ! &
        !-----------------------------------------------------!
105     PRINT "C L O U D 2   ";TIME$(0%);"     ";DATE$(0%) \ PRINT &
\       INPUT "DZ VALUE";DZ  \  PRINT &
\       INPUT "LEVELS NUMBER - MAXIMUM 60";LEV%  \  PRINT &
\       INPUT "TIME STEPS - MAXIMUM 250";STEPS%  \  PRINT &
\       INPUT "FILE NUMBER";D$ \ PRINT &
\       INPUT "CHANGE T(I,N) <YES> , <NO>";DD$  \  PRINT &
\         IF DD$="NO" &
          THEN 110 &
          ELSE INPUT "RANGE TO CHANGE";D
110     INPUT "IS DT CONSTANT <YES> , <NO>";DDT$ &
\       IF DDT$="NO" &
        THEN 200 &
        ELSE INPUT "DT VALUE";DT
200     !------------------------------------------------------! &
        !   P R I N T   D A T A                                ! &
        !------------------------------------------------------!
205     PRINT \ PRINT "           C O N S T A N T S" &
\              PRINT "     =========================" \ PRINT &
\       PRINT " ALFA=";ALFA";  A1=";A1;"  G=";G;"  CP=";CP;"  J=";J;&
        "  RC=";RC;"  EPS=";EPS;"  A=";A;"  TIME=";SUMTIM &
\       PRINT \ PRINT "           D A T A   F R O M   T E R M I N A L" &
\              PRINT "     ============================================="&
\       PRINT &
\       PRINT "   DZ=";DZ;"   LEVELS=";LEV%;"   STEPS=";STEPS%; &
\       PRINT "   FILE NUMBER=";D$ \ PRINT \ PRINT
250     !------------------------------------------------------! &
        !  OPENES FILES AND COPY DATA FROM FILES TO ARRAYS     ! &
        !------------------------------------------------------!
255     OPEN "CLTE."+D$ FOR INPUT AS FILE 1%,MODE 8192% &
\       INPUT #1%,TE(I%) FOR I%=1% TO LEV%  \  CLOSE 1% &
```

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```
\       OPEN "CLQE."+D$ FOR INPUT AS FILE 1%,MODE 8192% &
\       INPUT #1%,QE(I%) FOR I%=1% TO LEV%  \  CLOSE 1% &
\       OPEN "CLP."+D$ FOR INPUT AS FILE 1%,MODE 8192% &
\       INPUT #1%,P(I%,1%) FOR I%=1% TO LEV%  \  CLOSE 1% &
\       OPEN "CLT."+D$ FOR INPUT AS FILE 1%,MODE 8192% &
\       INPUT #1%,T(I%,1%) FOR I%=1% TO LEV%  \  CLOSE 1% &
\       OPEN "CLQS."+D$ FOR INPUT AS FILE 1%,MODE 8192% &
\       INPUT #1%,QS(I%) FOR I%=1% TO LEV%  \  CLOSE 1% &
\       OPEN "CLW."+D$ FOR INPUT AS FILE 1%,MODE 8192% &
\       INPUT #1%,W(I%,1%) FOR I%=1% TO LEV%  \  CLOSE 1% &
\       OPEN "CLR."+D$ FOR INPUT AS FILE 1%,MODE 8192% &
\       INPUT #1%,R(I%,1%) FOR I%=1% TO LEV%  \  CLOSE 1% &
\       OPEN "CLMU."+D$ FOR INPUT AS FILE 1%,MODE 8192% &
\       INPUT #1%,MU(I%,1%) FOR I%=1% TO LEV%  \  CLOSE 1% &
\       OPEN "CLRO."+D$ FOR INPUT AS FILE 1%,MODE 8192% &
\       INPUT #1%,RO(I%,1%) FOR I%=1% TO LEV% \ CLOSE 1%
400     !-----------------------------------------------------! &
        !     Z E R O S   A N D   U P D A T E   T(I,N)         ! &
        !-----------------------------------------------------!
405     MAT QC=ZER  \  MAT QH=ZER  \  MAT V=ZER &
\       MAT QSI=ZER  \  MAT DQS=ZER &
\       IF DD$="NO" &
        THEN 510 &
        ELSE T(I%,1%)=T(I%,1%)+D FOR I%=1% TO LEV%
500     !-----------------------------------------------------!&
        !   M A I N   L O O P - S T E P S   O F   T I M E     !&
        !-----------------------------------------------------!
510     FOR T%=1% TO STEPS%  !     T% - TIME INDEX &
\       DEG%=0%  \ E1=0
515        FOR I%=1% TO LEV% !    CALCULATE  DT  &
\          IF W(I%,1%)>E1 THEN E1=W(I%,1%)
520        NEXT I%
525     DT=DZ/E1 IF DDT$="NO"
526     SUMTIM=SUMTIM+DT
550     FOR I%=1% TO LEV%      !   I% - LEVELS INDEX &
\       IN%=I%+1%  \  IM%=I%-1%  \  IF T%=1% THEN 580
560     !---------------------------------------------------------!&
        !   C A L C U L A T E   Q S   W A T E R   E Q. 40         !&
        !---------------------------------------------------------!
565     E1=LOG10(T(I%,1%)) &
\       E2=-2937.4/T(I%,1%)-4.9283*E1+22.5518 &
\       E3=0.0001*P(I%,1%) &
\       QS(I%)=(EPS/E3)*(10**E2)
580     !---------------------------------------------------------!&
        !   C A L C U L A T E  Q S  I C E     E Q. 41             !&
        !---------------------------------------------------------!
585     E1=-2667/T(I%,1%)+9.5553 &
\       E3=0.0001*P(I%,1%) &
\       QSI(I%)=(EPS/E3)*(10**E1)
586     !---------------------------------------------------------!&
        !   C A L C U L A T E   D Q S    E Q.  42                 !&
        !---------------------------------------------------------!
587     DQS(I%)=QS(I%)-QSI(I%) &
\       IF I%=1% &
        THEN 590 &
        ELSE 600
590     T(1%,2%)=T(1%,1%) &
\       P(1%,2%)=P(1%,1%) &
```

```
\       R(1%,2%)=R(1%,1%) &
\       RO(1%,2%)=P(1%,2%)/(RC*T(1%,2%)) &
\       W(1%,2%)=W(1%,1%) &
\       MU(1%,2%)=2*ALFA/R(1%,2%) &
\               GO TO 2000     !    TO  NEXT  I%
600     !------------------------------------------------------! &
        !    CALCULATE  T  -  EQ. 49                           ! &
        !------------------------------------------------------!
601     IF I%<>LEV% &
        THEN 605 &
        ELSE IF T(I%,1%)>T(IM%,1%) &
             THEN T(IN%,1%)=2*T(I%,1%)-T(IM%,1%) &
             ELSE T(IN%,1%)=0.9*T(I%,1%)
605     LA=677  \  LF=80  \  LS=677 &
\       IF T(I%,1%)>273 THEN LA=595  \  LF=0  \  LS=0
610     E1=T(IN%,1%)-T(I%,1%) &
\       E2=((T(IN%,1%)+T(IM%,1%))/2)-W(I%,1%)*(DT/DZ)*E1 &
\       E3=W(I%,1%)*DT &
\       E4=(A1*G/CP)*(1+QS(I%)*LA*J)/(RC*T(I%,1%)) &
\       E5=MU(I%,1%)*(T(I%,1%)-TE(I%)) &
\       E6=MU(I%,1%)*(LA/CP)*(QS(I%)-QE(I%)) &
\       E7=1+((EPS*(LA**2)*QS(I%))/(CP*A1*RC*(T(I%,1%)**2))) &
\       E8=LF*(QC(I%,1%)+QH(I%,1%)) &
\       E9=LS*DQS(I%) &
\       E10=1/CP &
\       T(I%,2%)=E2-E3*(E4+E5+E6)/E7-E10*(E8+E9)/E7
650     !-------------------------------------------------------! &
        !     CALCULATE   QC -  EQ.50                           ! &
        !-------------------------------------------------------!
655     K1=0.0015  \  K2=0.0696 &
\       IF T(I%,1%)>273 &
        THEN K1=0.00075  \  K2=0.0052
660     IF I%<>LEV% &
        THEN 665 &
        ELSE IF QC(I%,1%)>QC(IM%,1%) &
             THEN QC(IN%,1%)=2*QC(I%,1%)-QC(IM%,1%) &
             ELSE QC(IN%,1%)=0.9*QC(I%,1%)
665     E1=(QC(IN%,1%)+QC(IM%,1%))/2 &
\       FOR X%=IM% TO IN% &
\       IF E1<QC(X%,1%) &
        THEN E1=QC(X%,1%)
666     NEXT X%
667     E1=E1-W(I%,1%)*(DT/DZ)*(QC(IN%,1%)-QC(I%,1%)) &
\       E2=G*W(I%,1%)*QS(I%)*DT/(RC*T(I%,1%)) &
\       E3=EPS*LA*J*QS(I%)*DT/(RC*(T(I%,1%)**2)) &
\       E4=(T(I%,2%)-T(I%,1%))/DT+(W(I%,1%)/DZ)*(T(IN%,1%)-T(I%,1%)) &
\       E5=MU(I%,1)*W(I%,1%)*DT*(QS(I%)-QE(I%)+QC(I%,1%)) &
\       E9=RO(1%,1%)/RO(I%,1%) &
\       E7=K2*DT*(E9**0.5)*(RO(I%,1%)**E78)*QC(I%,1%)*(QH(I%,1%)**E78) &
\       QC(I%,2%)=E1-E2-E3*E4-E5-E7 &
\       E8=K1*DT*(QC(I%,1%)-(A/RO(I%,1%))) &
\       IF QC(I%,1%)>(A/RO(I%,1%)) &
        THEN QC(I%,2%)=QC(I%,2%)-E8
669     IF QC(I%,2%)<0 &
        THEN QC(I%,2%)=0
700     !---------------------------------------------------! &
        !      CALCULATE   QH  -  EQ. 52                    ! &
        !---------------------------------------------------!
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 IX=LEVX &
:N 710 &
;E 725
 QH(IX,1X)>QH(IMX,1X) &
:N QH(INX,1X)=2*QH(IX,1X)-QH(IMX,1X) &
;E QH(INX,1X)=0.9*QH(IX,1X)
 RO(IX,1X)>RO(IMX,1X) &
:N RO(INX,1X)=2*RO(IX,1X)-RO(IMX,1X) &
;E RO(INX,1X)=0.9*RO(IX,1X)
 V(IX,1X)>V(IMX,1X) &
:N V(INX,1X)=2*V(IX,1X)-V(IMX,1X) &
;E V(INX,1X)=0.9*V(IX,1X)
)=W(IX,1X)+V(IX,1X) &
=(QH(INX,1X)+QH(IMX,1X))/2 &
=E1-E10*(DT/DZ)*(QH(INX,1X)-QH(IX,1X)) &
=V(IX,1X)*(LOG(RO(INX,1X))-LOG(RO(IX,1X)))/DZ &
=(V(INX,1X)-V(IX,1X))/DZ &
=MU(IX,1X)*W(IX,1X)*QH(IX,1X) &
=K1*(QC(IX,1X)-(A/RO(IX,1X))) &
=RO(1X,1X)/RO(IX,1X) &
=K2*(E8**0.5)*(RO(IX,1X)**E78)*(QH(IX,1X)**E78) &
(IX,2X)=E1+DT*(-QH(IX,1X)*(E3+E4)-E5+E9) &
 QC(IX,1X)>(A/RO(IX,1X)) &
EN QH(IX,2X)=QH(IX,2X)+(DT*E6)
 QH(IX,2X)<0 &
IEN QH(IX,2X)=0
------------------------------------------------------------! &
      C A L C U L A T E   V - E Q. 51                       ! &
------------------------------------------------------------!
 T(IX,1X)<=273 &
IEN K3=15.39 &
.SE K3=11.58
 QH(IX,2X)<=0 &
IEN V(IX,2X)=0 &
.SE V(IX,2X)=K3*(QH(IX,2X)**0.125)*(-130)
------------------------------------------------------------! &
      C A L C U L A T E   W - E Q.  53                      ! &
------------------------------------------------------------!
 IX=LEVX &
IEN IF W(IX,1X)>W(IMX,1X) &
   THEN W(INX,1X)=2*W(IX,1X)-W(IMX,1X) &
   ELSE W(INX,1X)=W(IX,1X)/2+1
.=W(IX,1X)*(W(INX,1X)-W(IX,1X))*DT/DZ &
!=(1+0.61*QS(IX))*T(IX,1X) &
;=(1+0.61*QE(IX))*TE(IX) &
)=QC(IX,1X)+QH(IX,1X) &
;=MU(IX,1X)*(W(IX,1X)**2)*DT &
,=(E2-E3)/E3 &
IX,2X)=(W(INX,1X)+W(IMX,1X))/2-E1+DT*G*(E6-E4)-E5 &
 W(IX,2X)>0 &
IEN 820 &
.SE LEVX=IX-1X  \  DEGX=1X
---------------------------------------------------------------! &
       C A L C U L A T E  R  -  E Q.  54                       ! &
---------------------------------------------------------------!
 IX=LEVX &
IEN IF R(IX,1X)>R(IMX,1X) &
   THEN R(INX,1X)=2*R(IX,1X)-R(IMX,1X) &
```

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          ELSE R(IN%,1%)=0.9*R(I%,1%)
10     E1=W(I%,1%)*DT*(R(IN%,1%)-R(I%,1%))/DZ &
       E2=ALFA*DT*W(I%,1%) &
       E3=W(I%,1%)*R(I%,1%)*DT/2 &
       E4=(LOG(W(IN%,1%))-LOG(W(I%,1%)))/DZ &
       E5=(LOG(RO(IN%,1%))-LOG(RO(I%,1%)))/DZ &
       R(I%,2%)=(R(IN%,1%)+R(IM%,1%))/2-E1+E2-E3*(E4+E5)
0      !------------------------------------------------------------! &
       !       C A L C U L A T E   P  -  E Q.  46                    ! &
       !------------------------------------------------------------!
5      E1=-G/RC   \   E2=0 &
       FOR J%=1% TO I% &
       IF T(J%,2%)<>0 &
       THEN E2=E2+DZ/T(J%,2%)
.0     NEXT J%
.5     E3=E1*E2 &
       P(I%,2%)=P(1%,2%)*EXP(E3)
0      !------------------------------------------------------------! &
       !       C A L C U L A T E      R O   EQ. 45                   ! &
       !------------------------------------------------------------!
5      RO(I%,2%)=P(I%,2%)/(RC*T(I%,2%))
0      !------------------------------------------------------------! &
       !       C A L C U L A T E      M U  -  E Q. 1                 ! &
       !------------------------------------------------------------!
5      MU(I%,2%)=2*ALFA/R(I%,2%) &
                                       IF DEG%=1% &
                                       THEN 2001 &

00     NEXT I%      !          E N D   L E V E L S   L O O P      !

01     !------------------------------------------------------------! &
       !        P R I N T      R E S U L T S                        ! &
       !------------------------------------------------------------!
02     PRINT "            OUTPUT - STEP OF TIME ";T%;" TIME=";SUMTIM; &
       "  LEVELS=";LEV% &
       IF T%=1% OR T%-(T%/5%)*5%=0% &
       THEN 2005 &
       ELSE 2200
05     PRINT &
       PRINT "            OUTPUT - STEP OF TIME ";T%;" TIME=";SUMTIM; &
       "  LEVELS=";LEV% &
       PRINT "      ====================================================="; &
       "============="
00     FOR J%=1% TO 2% &
       PRINT &
       IF J%=1% &
       THEN PRINT ST1$ &
       ELSE PRINT ST2$
15     PRINT ST3$ &
       IF J%=2% &
       THEN 2140
20     FOR L%=1% TO LEV% &
             PRINT USING ST4$,L%,T(L%,2%),W(L%,2%),R(L%,2%),&
                                P(L%,2%),QC(L%,2%),QH(L%,2%) &
       NEXT L% &
                       GO TO 2150
40     FOR L%=1% TO LEV% &
             PRINT USING ST4$,L%,RO(L%,2%),MU(L%,2%),V(L%,2%), &
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```
                    QS(L%),QSI(L%),DQS(L%) &
\       NEXT L% \ PRINT \ PRINT

2150    NEXT J%
2200    !-------------------------------------------------------------! &
        !      TRANSFER  FROM  COLUMN  2  TO  COLUMN  1               ! &
        !-------------------------------------------------------------!
2210    IF LEV%=1% THEN 10000   !          S T O P       R U N        !
2215    FOR J%=1% TO LEV% &
\       T(J%,1%)=T(J%,2%)  \  QC(J%,1%)=QC(J%,2%)  \  QH(J%,1%)=QH(J%,2%) &
\       W(J%,1%)=W(J%,2%)  \  R(J%,1%)=R(J%,2%)    \  P(J%,1%)=P(J%,2%) &
\       MU(J%,1%)=MU(J%,2%)\  RO(J%,1%)=RO(J%,2%) \ V(J%,1%)=V(J%,2%) &
\       NEXT J%

3000    NEXT T%   !    E N D    T I M E    L O O P                    !
10000   END
```

Acknowledgment

Mr. Aharon Baruch, of Kibbutz Sede Boqer, did the programming. I wish to thank him for his outstanding efforts in getting the program to work, under very adverse conditions of computer availability.

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